P.A.L.M:

Physical Asset Life Cycle Modelling in the Healthcare Sector

Amir Nabil

Institute for Environmental Design and Engineering

The Bartlett Faculty for the Built Environment

University College London

A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Engineering

University College London

University of London

2016

Statement of Original Authorship

I, Amir Nabil, confirm that the work contained in this thesis has not been previously submitted to meet the requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

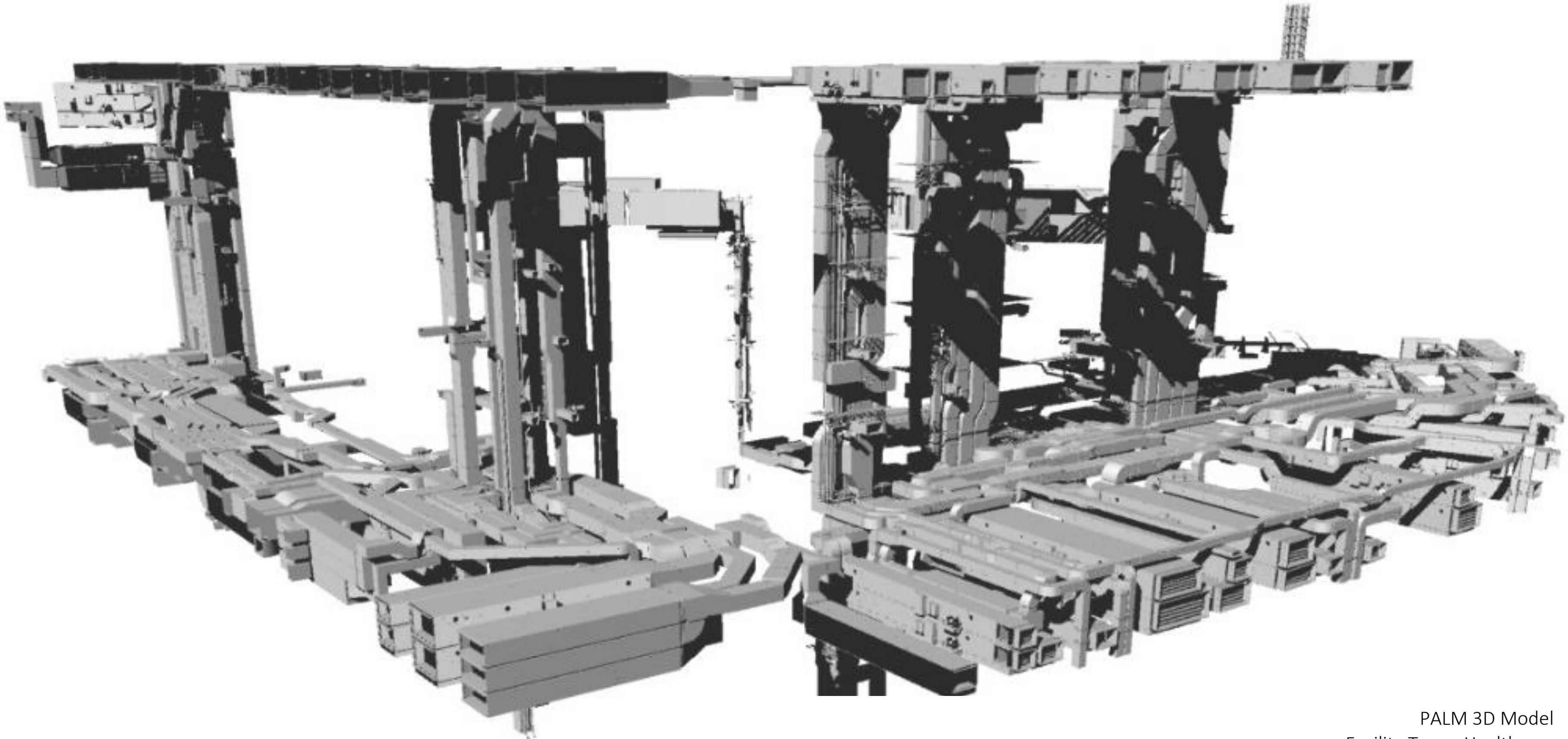
Signature: ___________________________

Date: ___________________________

PALM

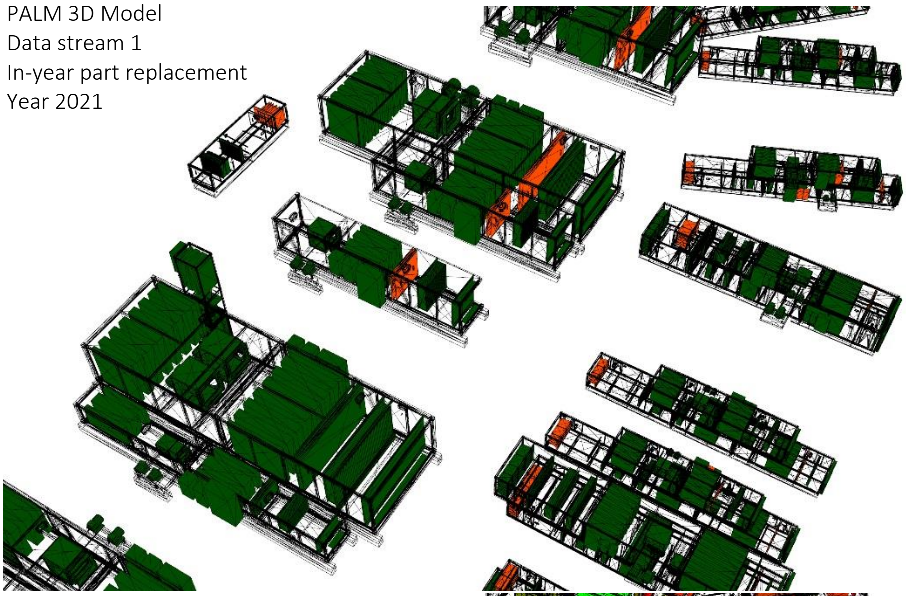
Physical Asset Lifecycle Modelling

www.palmvisual.co.uk

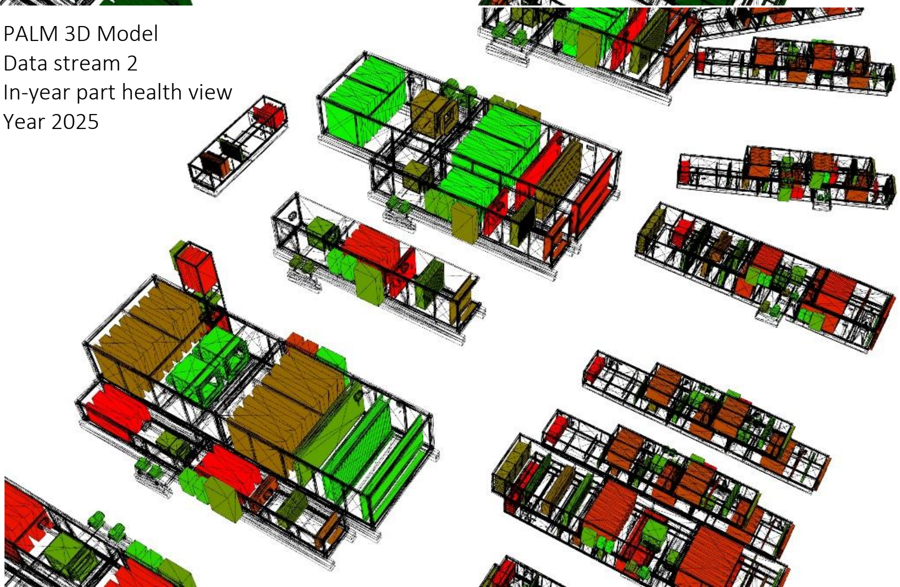


PALM 3D Model
Facility Type - Healthcare
System – Space Heating and Ventilation
Asset – Air-Handling Unit
Asset Number – 113
Number of Subcomponents – 1247
Current budget for maintaining system - £6,045,000

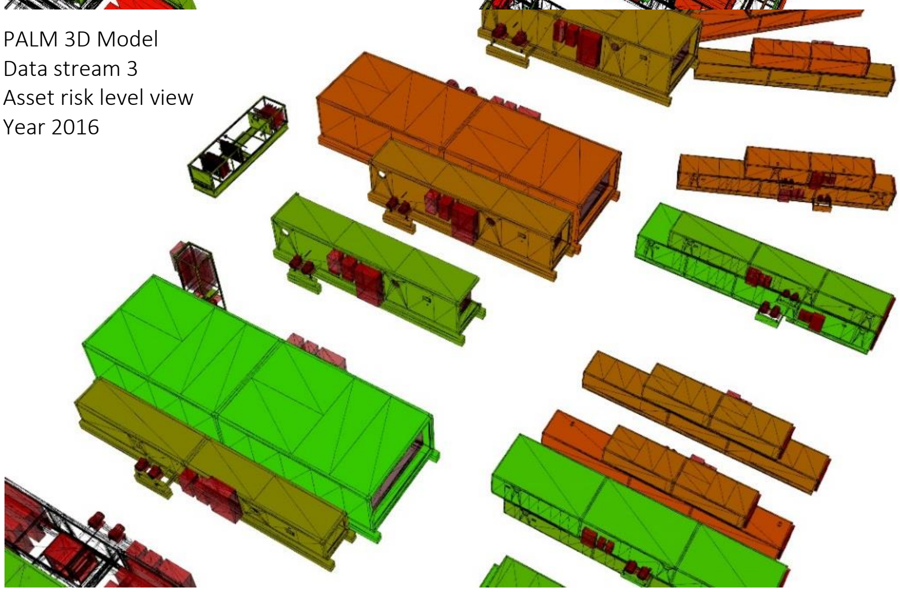
PALM 3D Model
Data stream 1
In-year part replacement
Year 2021



PALM 3D Model
Data stream 2
In-year part health view
Year 2025

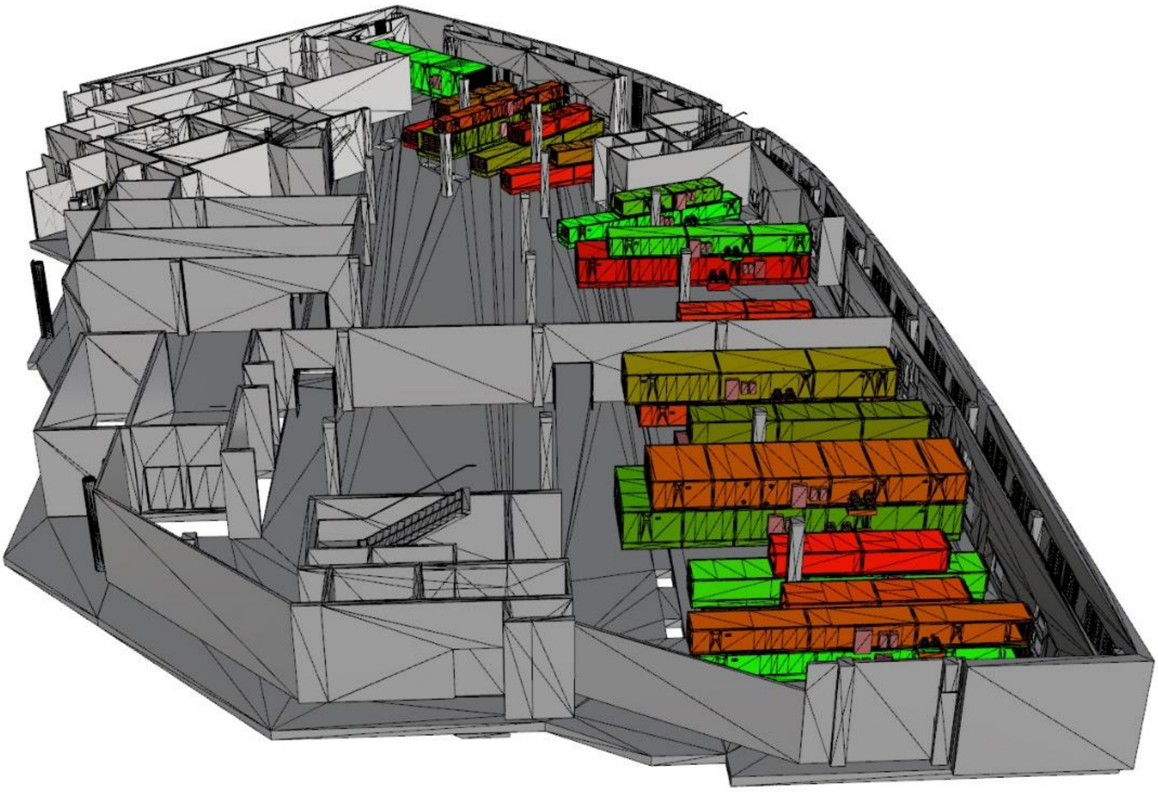


PALM 3D Model
Data stream 3
Asset risk level view
Year 2016



Keywords

Asset management, BIM, decision-making, Grasshopper simulation, lifecycle costing, lifecycle modelling, probabilistic models, risk-management, Rhino5.



PALM 3D Model
Asset Risk Level Viewer
Second Floor – Phase One
Facility Type - Healthcare
System – Space Heating and Ventilation
Asset – Air-Handling Unit

Preface

This thesis presents research conducted between 2013 and 2016 under the Engineering and Physical Sciences Research Council's (EPSRC) Doctor of Engineering (EngD) scholarship. This thesis fulfils the requirements of an EngD degree at the Institute of Environmental Design and Engineering (IEDE) at University College London. The research was based at Modus Services Limited and HCP Social Infrastructure UK, the industrial sponsor for the doctorate. Funding for the research was obtained from EPSRC and Modus Services Limited, London.

The key component in the award of the EngD and the core of the research lies in solving significant and challenging engineering problems within the industrial context. The thesis is underpinned by the risk theme and discusses approaches to decision-making with reference to the life management of assets. Risk-based approaches as applied to the life management of air-handling units and their subcomponent parts are discussed in this thesis. Papers and conferences have been produced/attended as a by-product of the ongoing research over the years. The earlier papers and conferences attended pointed to the primary topic of artificial intelligence algorithmic control of the air-handling units; however, the trajectory of the work altered during the first year of the EngD to incorporate risk, currently seen as the core concern of the industrial sponsors business. The papers are referenced within the thesis where necessary.

Abstract

A Private Finance Initiative (PFI) is a way of establishing Public-Private Partnerships (PPP) by funding public infrastructure projects with private capital investment. The election in 1979 of a Conservative government under Margaret Thatcher marked the start of a still-continuing shift of activities away from the UK public sector. PFI was implemented in the UK for the first time in 1992.

HCP is an award winning PFI asset-management company and, as part of the EngD course, the researcher has spent a large amount of time based at HCP. HCP stands for Healthcare Projects, and this thesis presents an alternative, combined-methods research approach to one of the most mechanically complex asset types under HCP's management, in its largest healthcare facility. The research presents a risk-based approach to the operational lifecycle planning of 113 air-handling units at a central London hospital. The two components to the project are engineering risk (*How likely is the asset to fail?*) and contractual risk (W*hat are the financial implications of such a failure?*). Currently, these assets are modelled by HCP on a 'strategic' level, but using CIBSE-recommended guidance and part-failure data collected from six other UK-based hospitals, the Physical Asset Lifecycle Model (PALM) produces a funding profile for the replacement of the 1,247 internal components, as opposed to 113 bulk assets. The numerical model has also been visualised through the extraction of 3D BIM geometry into a geometrical-modelling tool (Rhino5) and computational plug-in (Grasshopper) to connect to the lifecycle model and visualise the replacement strategy proposed. The qualitative part of the combined-methods approach involved interviewing HCP Management board members as to their views on the models.

The current profile adopted by HCP for the management of the air-handling units involves a £6.045m spend during the remaining 33-year concession period. The main findings of the PALM lifecycle model are that, based on a component-level replacement approach, this figure can be reduced by more than £1m based on a *recommended* replacement profile (£4.709m). Such a reduction can be based on how HCP currently manages its assets, and the engineering survey conducted showed that three air-handling units currently being life-cycled by HCP either had no components or were decommissioned prior to construction. The main findings of the PALM geometrical model (based on thematic-interview analysis) are that such a tool has largely been unseen in the industry before and it displays major translatability to other complex mechanical assets with component parts. It can also be integrated into HCP business propositions for new and existing clients in the future because of its clarity and ability to produce transparent lifecycle modelling from a decision-maker's point of view.

The research concludes that while the PALM model provides a glimpse as to how lifecycle modelling may be conducted in the future, a number of barriers to its implementation remain (namely data availability in a competitive environment, the *time versus income generated* business-case paradigm and a generational ability to change and accept technological advancements amongst senior decision-makers).

Acknowledgements

I would like to thank Professor Michael Pitt (UCL), Mr Peter McLennan (UCL) and Dr Michael Emes (UCL) for their help and encouragement throughout this thesis.

I would also like to thank Ms Chrysa Varna (Troika), Dr Sean Hanna (UCL) and Ms Martha Tsigkari (Foster+Partners) for their assistance at times throughout the past four years.

Thanks to Modus Services Ltd, HCP Social Infrastructure UK and the Engineering and Physical Sciences Research Council (EPSRC) for their generous support throughout.

Thanks to the Engineering Doctorate Board members who critically appraised and nurtured the progress of this research, namely Mr Paul Francis (Modus Services Limited), Mr Terry Rolfe (Skanska), Mr Wayne Partington (Modus Services Limited), Professor Michael Pitt, Mr Christian Betts (Modus Services Limited), and my fellow Engineering Doctorate candidates Mr Ruhul Amin (UCL/ Skanska) and Mr Kieran Mulholland (UCL/ HCP). The only two other people who truly know the degree to which we apply ourselves.

I would like to thank Alan Brazil (of Alan Brazils Sports Breakfast), Adrian Durham and Darren Gough (of Drivetime), and Andy Goldstein, The Gouldfather and Jason Cundy (of The Sports Bar) and the rest of the team at talkSPORT for keeping the morale high throughout.

Finally, I would like to thank my parents and brothers, Mr Driss Nabil, Mrs Alison Nabil, Mr Tariq Nabil and Mr Shakir Nabil for their tremendous support and patience during my time spent in this bubble. I love you all and this is for you.

Table of Contents

List of Figures

List of Tables

List of Equations

List of Abbreviations

AHU	Air-Handling Unit
AIM	Asset Information Modelling
AMP	Asset Management Plan
ANN	Artificial Neural Network
ARMA	Auto-Regressive Moving Average
B&ES	Building and Engineering Services Association
BIM	Building Information Modelling
BIS	Department of Business Innovation and Skills
BM	Building Maintenance
BVM	Building Valuation Model
CAPEX	Capital Expenditure
CAVE	Computer Automated Virtual Environment
CBA	Cost-Benefit Analysis
CBR	Case Based Reasoning
CD	Current Deficiencies
CRV	Current Replacement Value
DL	Design Life
DM	Deferred Maintenance
DoI	Department of Industry
EAM	Enterprise Asset Management
EFCI	Extended Facility Condition Index
EngD	Engineering Doctorate
ESL	Estimated Service Life
FCI	Facility Condition Index
FMEA	Failure Modes Effect and Analysis
FMECA	Failure Modes Effect and Criticality Analysis
FNI	Facility Needs Index
FRR	Facility Revitalisation Rate
HVAC	Heating, Ventilation and Air Conditioning
IAM	Institute of Asset Management
IFPI	International Facilities and Property Information
KM	Knowledge Management
KPI	Key Performance Indicator
LC	Lifecycle
LCAM	Lifecycle Actuarial Model
MC	Monte Carlo
MEP	Mechanical and Electrical Plant
MPM	Mathematical Parametric Model
MSP	Management Service Provider
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NACUBO	National Association of College and University Business Officers
NFCI	Normalised Facility Condition Index
NPV	Net Present Value

NRM	New Rules of Measurement
OCC	Observational Catch-up Cost
OPEX	Operational Expenditure
PFI	Private Finance Initiative
PPM	Planned Preventative Maintenance
PPP	Public Private Partnership
PreFCI	Preliminary Facility Condition Index
ProjFCI	Projected Facility Condition Index
PSC	Public Sector Comparator
RBI	Reliability Based Inspection
RCA	Root Cause Analysis
RCM	Reliability Centred Maintenance
RI	Requirements Index
RM	Reactive Maintenance
ROCC	Roll-Over Catch-up Cost
RPI	Retail Price Index
RSL	Remaining Service Life
RUL	Remaining Useful Life
RV	Replacement Value
SAM	Strategic Asset Management
SF	Square Feet
SMM	Standard Method of Measurement
SPV	Special Purpose Vehicle
SRM	System Renewal Method
TCC	Transitional Catch-up Cost
UFCI	Updated Facility Condition Index
UK	United Kingdom
VEIV	Virtual Environments Imaging and Visualisation
VFM	Value For Money
WFCI	Weighted Facility Condition Index
WLC	Whole Life Costing

Chapter 1. Introduction

1.1 Research Purpose within a Private Finance Initiative

This thesis researches the risk-based life replacement of mechanical assets (specifically air-handling units (AHUs)) and their subcomponent parts within the operational life of a healthcare project. Life management, otherwise known as lifecycle replacement, falls under the umbrella of Strategic Asset Management (SAM) and is concerned with the efficient management of complex assets during their life. Mechanical and Electrical (M&E) equipment is often complex and, when installed in a high criticality environment such as a hospital, can experience intensive usage above and beyond expected norms. As a result of such usage-patterns, mechanical equipment in particular can be more susceptible to sudden failures and reduced life-spans. Their susceptibility to failure in conjunction with their criticality may have different implications to that of their non-mechanical counterparts. The issue of *specific areas and zones* within a hospital that are served by air-handling units also contributes to the complexity of the replacement assumption problem.

Life replacement strategies include activities which can affect the replacement life of an asset, such as its runtime and its priority within the business' ability to ensure resilience and continuity. There are numerous approaches to estimating the time at which an asset should be replaced; it can be run to failure or replaced as part of a Planned Preventative Maintenance (PPM) policy. However, this level of detail is not the concern of this thesis. Instead of focusing on day-to-day operations, this thesis considers aspects of the operational continuum and the central focus is on those stakeholders outside operations with a large decision-making ability likely to affect a facility's long-term success.

The scope of this research project will take a Private Finance Initiative (PFI) standpoint and all research conducted has taken place within this environment. The PFI business model and its implications have been discussed widely in recent literature (Hartman, 2004; Kierulff, 2007; Reynaers & De Graaf, 2014; Richardson, Kefford, & Hodkiewicz, 2013; Scharle, 2002). A PFI is a way of establishing public-private partnerships (PPP) by funding public infrastructure projects with private capital investment. The contracts and structure of PFIs are unique to the construction infrastructure and facilities management industry. As a rule of thumb, PFI contracts are typically 25 to 30 years in length and, although contracts of less than 20 years or more than 40 years exist, they are considerably less common. This contract term length coupled with the increased usage of PFI contracts adds considerable complexity to the contractual process and context. PFI initiatives can contain either explicit contractual options or implicit options not stated in the contract. When this is considered in addition to Cost-Benefit Analyses (CBA) Net Present Value (NPV) criterion and external political considerations, the issue of private dynamic decision-making at a point in time is exacerbated because of increasing future uncertainty (Krüger, 2012). A number of private sector investors, usually a construction company and a service provider and often a bank owns a consortium, otherwise known as a Special Purpose Vehicle (SPV), as well (Zheng et al., 2008). Figure 1 illustrates the interconnected relationship between SPV, Authority and Management Service Provider (MSP) in the context of this research. The management of assets from an MSP's point of view can be more appropriately illustrated through the relationship diagram shown in Figure 2. The research adopts the position from the standpoint of the MSP, which is an overarching organisation that manages the asset strategy on a portfolio-wide basis and provides a service to each individual SPV. The MSP provides service management in the form of creative, intelligent asset management solutions to the built environment by increasing efficiency and minimising risk for the client. The MSP's successful provision of more robust, intelligent asset management is achieved through building close working relationships with project stakeholders, including public sector clients, FM providers, and construction and equity funding companies.

This research attempts to develop a technique which will more accurately reflect the ongoing lifecycle investment necessary within a PFI-owned and operated NHS trust hospital. Previous research has been done in this area (Kirkham, 2002). This study is unique because it is research presented from the point of view of the private financiers and focuses on the lifecycle replacement strategy, known as Lifecycle Costing (LCC). Currently, LCC is a technique primarily used for investment decision-making at the pre-construction phase, and often forms a large part of a financial model prior to construction. In the case of PFI, LCC is often assumed to be 'flat-lined' because prior to completion there is very little known about usage levels of assets that are to be installed. With completion and commencement of operations, more information is known about the assets, and this presents an opportunity to more accurately model the expected replacement life of the parts. Here it is proposed that LCC can also be used as a tool for investment decision-making and facility management in existing hospital estates. The goal is to develop a model which produces a single LCC figure as an output for 113 an air-handling units and a key concept within the research looks at the parts that lead to the final figure and how they can be altered dependent on the decision-maker's 'risk appetite'. The overall LCC for an air-handling unit can be ascertained on an asset system or component level. This model supports the latter and can provide a platform for future expansion to include other mechanical and electrical assets using the same method (i.e. the model offers high translatability of results across differing asset systems). The development of a set of key principles in this work enables the end user to have a more accurate view on the costs incurred per financial year, through associating all costs to specific asset components, rather than the asset system. While there may still be an under-funding or over-funding issue, the asset manager is more aware of what strategic decision-makers have budgeted for in any given year, improving accountability and providing transparency between organisational levels.

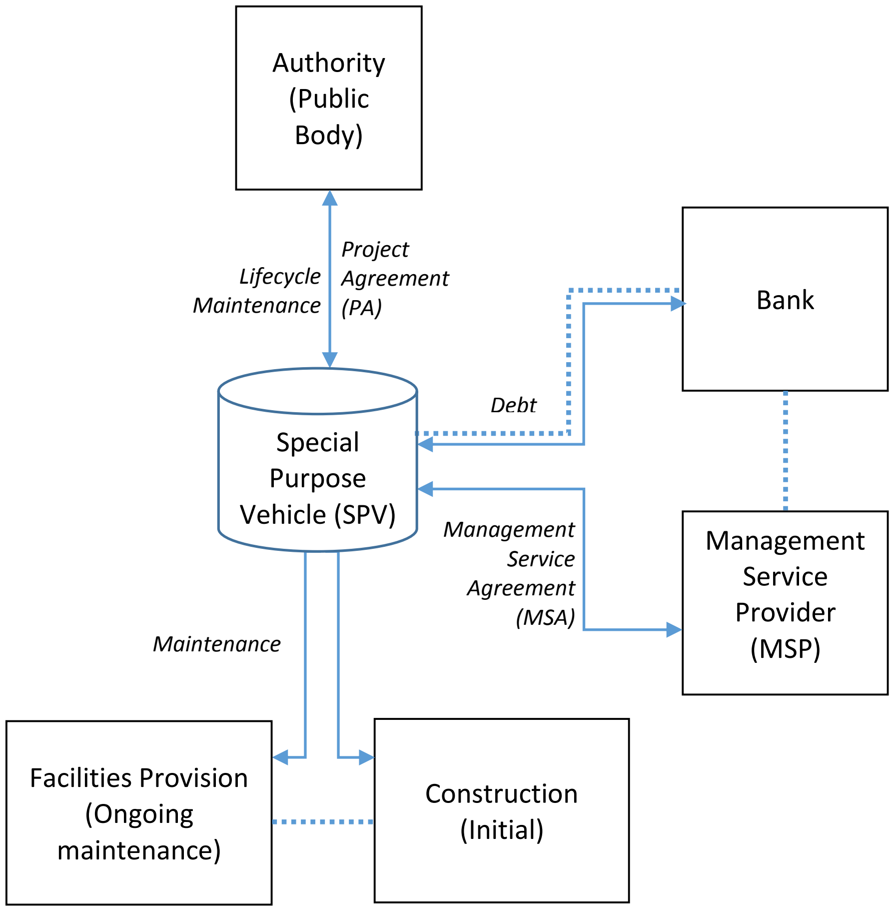


Figure 1: Relationship diagram between MSP, SPV and the Authority

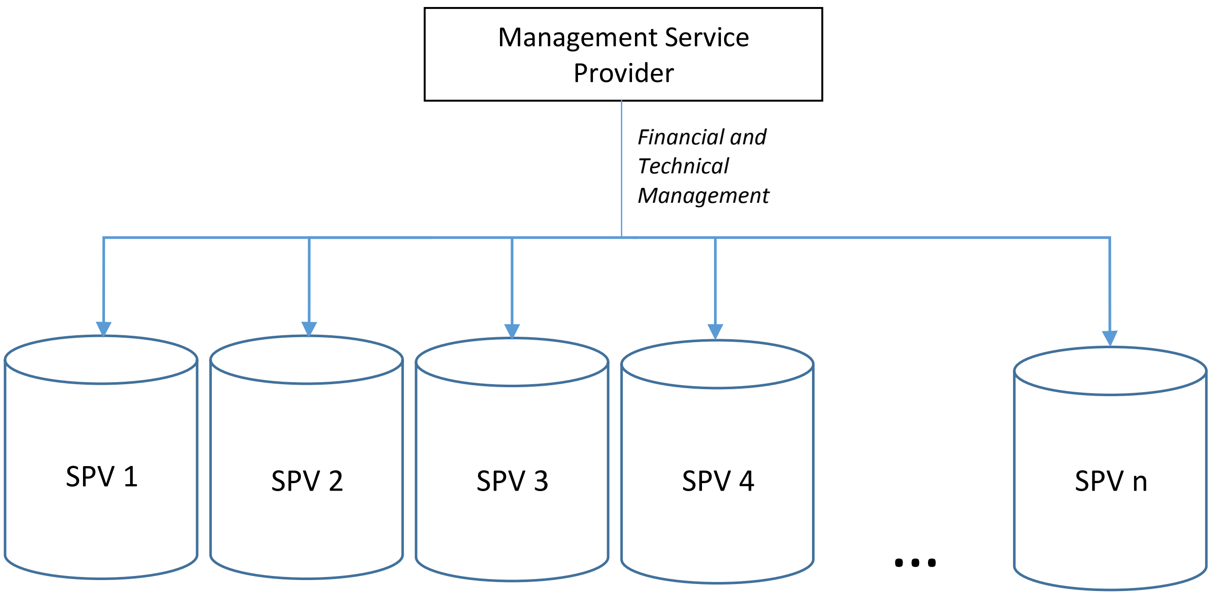


Figure 2: Relationship diagram between MSP and SPV

1.2 The Research Problem

The research problem is centred around air-handling units within a PFI healthcare facility in Central London. This healthcare facility shall be known as HCP1 and is the testing facility. No-one actually knows what assets will fail and when, so it is commonplace for 'allowances' to be made in each financial year based on a survey process. The survey is used to identify the current performance of the estate in terms of physical condition and statutory compliance.

The condition survey of the facility provides a great deal of information and constitutes an essential base from which maintenance and capital investment strategies can be formulated (Kirkham, 2002). The survey involves assessing each asset as per the categories shown in Table 1.

Table 1: Condition definitions

Condition Definition	Classification	FCI
As new and can be expected to perform adequately to its full normal life	**A**	< 5 %
Sound, operationally safe and exhibiting only minor deterioration	**B**	6 – 11 %
Currently as B but will fall below B within five years	**B (C)**	12 – 15 %
Operational but major repair or replacement is currently needed to bring up to condition B	**C**	16 – 30 %
Operationally unsound and in imminent danger of breakdown	**D**	31 – 59 %
Supplementary rating added to C or D to indicate that it is impossible to improve without replacement	**X**	> 60 %

Where A is defined as new and can be expected to perform adequately to its full normal life and D is defined as operationally unsound and in imminent danger of breakdown (excluding X – a supplementary rating to C and D). The surveyor is also required to record the remaining life of the component. This is an estimate and assumes that the element will continue to be maintained at the same level as in the past. The overall remaining life is calculated by using an average to arrive at a condition, expected replacement year and percentage replacement. As discussed in other research (Kirkham, 2002) this is a flawed approach, and does not take into account the rate of failure due to externalities and unique circumstances. Complex assets such as AHUs are observed non-intrusively, so their life prediction is done on an AHU level rather than component level.

If an AHU costs £500,000 and it is forecast that it will have a coil replacement the following year, an allowance (i.e. an estimated sum of money) will be ring-fenced for that particular project. There are two issues with this current type of forecasting. Firstly, due to manufacturers' reluctance to release data it is difficult to forecast exactly when a part will fail. So, many asset managers and management service consultancies will revert to the CIBSE Guide M. Secondly, approximate percentages of whole asset cost, rather than part cost, leads to confusion on the operational-level.

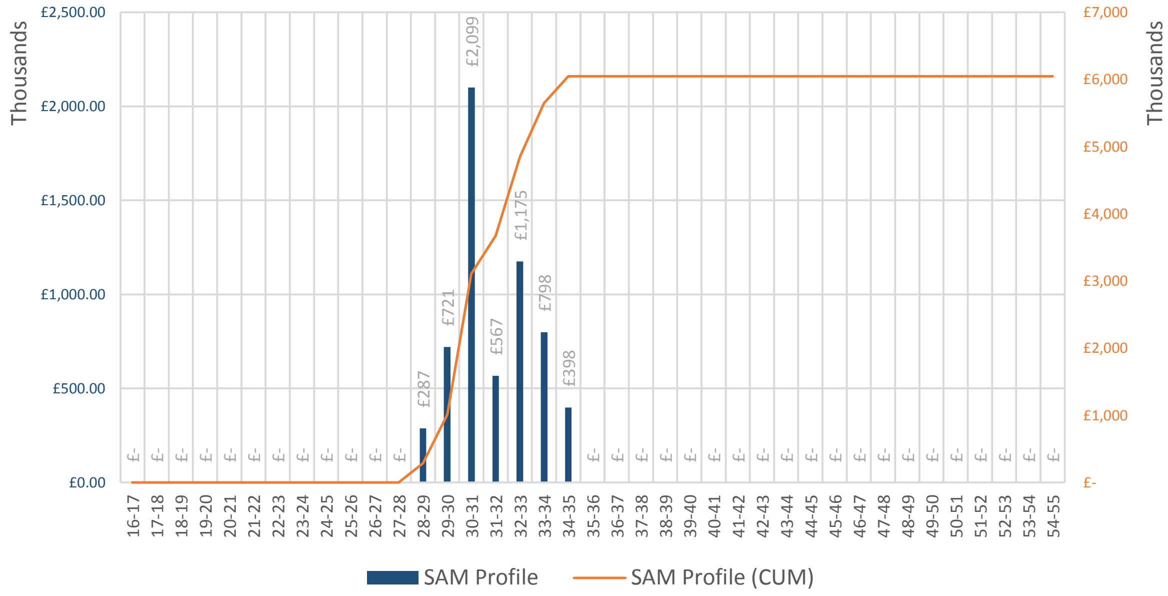


Figure 3: HCP current lifecycle profile for air-handling units

Table 2: HCP current lifecycle profile key metrics and statistics

Option Scenarios	Option C – Current
Inflation rate	Mean compounded RPI
Lifecycle Expenditure (Date -Mar 2048)	£6,045,470
Lifecycle Expenditure (Date -Mar 2053)	£6,045,470
Handback Requirements	£0
Mean Lifecycle/ annum (Date -Mar 2048)	£183,196
Mean Lifecycle/ annum (Date -Mar 2053)	£159,091
Mean Lifecycle/m2/annum (Date -Mar 2048)	£3.47
Mean Lifecycle/m2/annum (Date -Mar 2053)	£3.02
Peak Lifecycle Year	2030-31
Peak Lifecycle year foreseen expenditure	£2,099,212

Option C presents a lifecycle model funding profile for the 113 AHUs at HCP1 (Figure 3). The blue bars represent the lifecycle costs in-year and the orange line is the cumulative equivalent over the concession. The total cost of the replacement of the AHUs until the end of the contractual period is just over £6m. In terms of yield position, the common metrics by which a lifecycle fund is analysed are shown in Table 2.

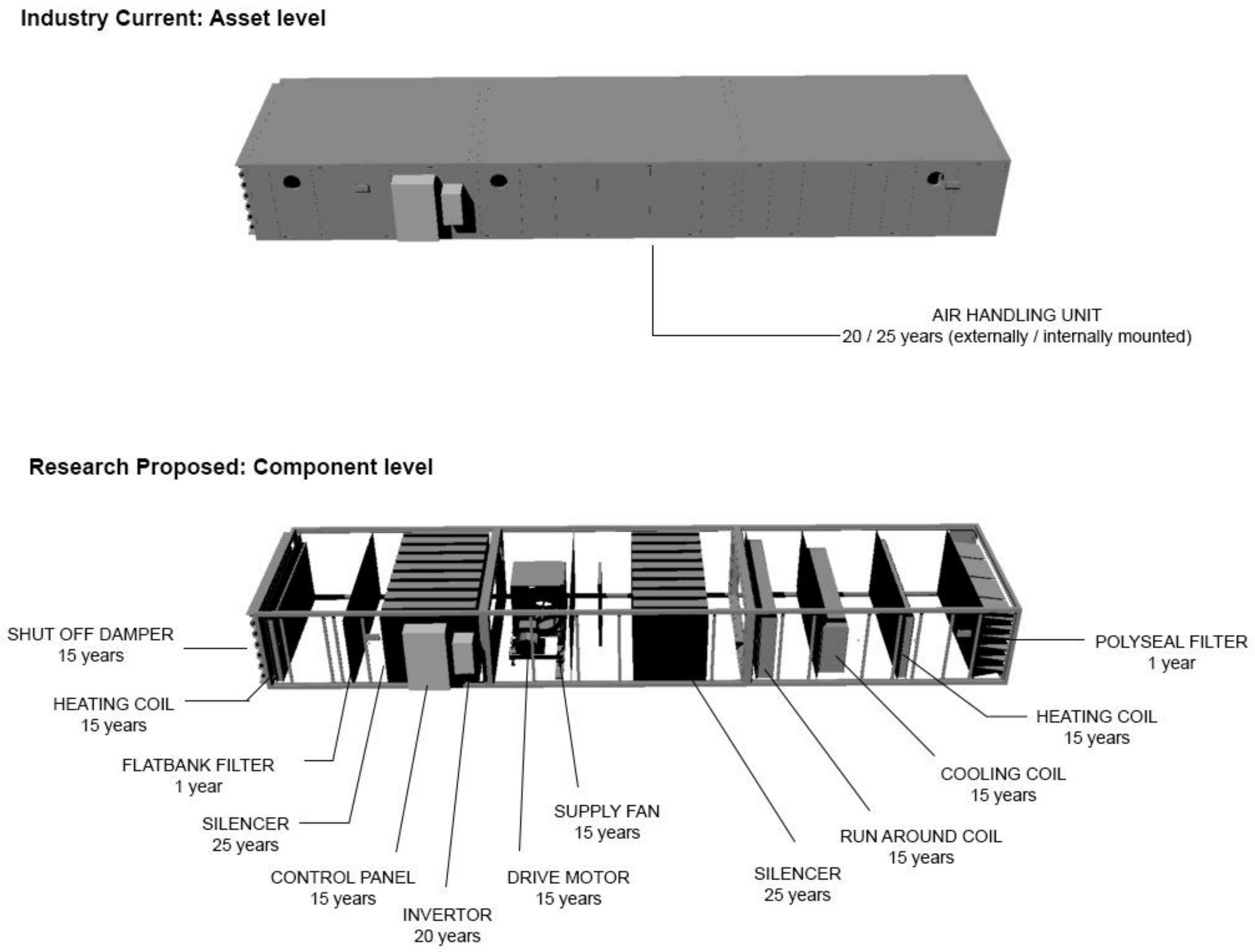


Figure 4: Industry current versus Research proposed lifecycle illustration

The peak amount of lifecycle works occurring in one year is circa £2.1m. The practicality of delivering £2.1m worth of lifecycle replacement works for the AHUs is unrealistic (over £8,000 per day). Spikes within a model can negatively impact the financial profile of the project from an accounting perspective. Having undesirable impacts with an overdrawing of capital to pay shareholders leaving potential shortfalls in years to come. There are also management considerations as a result of the current profile. The greatest lifecycle period (expected in year 30-31) is flanked by two yearly periods with less than half the outgoings (£721k and £567k). With space heating and ventilation expertise being a necessary pre-requisite for delivering the works operationally, this spike suggests an increase in staff followed by a removal of staff after the peak. The model does not provide a picture supportive of ongoing business continuity.

The upper half of Figure 4 demonstrates the level of detail which the air handling units are currently surveyed (the *Asset System Level*) and is a visual representation of the research problem. The lower half of Figure 4 demonstrates a *Component (or part) Level* approach to lifecycle costing. A new approach, using new tools and new data is necessary for the advancement of asset management.

1.3 Aim and Objectives

Standard LCC techniques, by their very nature, neglect the long-term uncertainty that is inherent in such a forecasting technique. Some have argued that the scale of the data collection exercise in itself prohibits a more comprehensive coverage of the risk element (Kirkham, 2002). However, the data collection hurdle is something which must be overcome in order to build more realistic and scientific LCC models. This research will delve into probabilistic-based economic distributions and 3-dimensional interactive visualisations for the lifecycle replacement strategy of a complex asset; an air-handling unit. Research is carried out at a UK hospital. The rationale for using air-handling units in the research is:

- It is a complex asset currently being lifecycle funded on an asset level. However, CIBSE recommends differing lifetimes for its constituent parts.
- Previous research and experience during the research Masters (MRes) focussed on air-handling units and so there is prior knowledge of the equipment.
- Through direct exposure to the hospital it is understood that the air-handling units are run so frequently that surveying (the current technique) the internal parts of the air-handling units is unachievable.

The aim of the research is:

To develop a data-driven risk-based lifecycle replacement funding model and visualisation tool to improve the decision-making of mechanical assets in the PFI Healthcare sector.

The research objectives are as follows:

- To create a model building approach based on a detailed understanding of the PFI business model and context.
- To develop a model to improve using the necessary factors to achieve the solution.
- To build a model that can be translated and expanded to other projects in future.
- To qualitatively collect and analyse feedback from stakeholders in the position of approving lifecycle works.

This research makes a contribution to knowledge in two ways:

- The use of new failure data establishes a lifecycle profile on a component level as yet unseen in the AM industry.
- The visualisation of lifecycle works within a PFI and wider context is unique and uses a new modelling tool and methodology.

1.4 Research Structure and Chapter Layout

Chapter 1: Research Introduction, Contextual Position and Structure

An introduction to the study discussing the relevant background of the research, the research aim, questions and objective arising and the main structure of the thesis are outlined.

Chapter 2: Asset management and Life Cycle Costing

A discussion around the area of Asset Management, key definitions, current metrics of measuring facility lifecycle costs and alternative methods of calculating lifecycle.

Discusses the key costs within a facility lifecycle, from construction to disposal. Current service life estimation methods and data sources acceptable for building lifecycle models.

Chapter 3: The Role of Risk is Lifecycle Costing and Service Life Prediction

Discusses risk in the context of PFI AM. The types of risk from a management perspective to technical risk over time as visualised through the bathtub curve.

Chapter 4: Visual Modelling – The Transition from Construction to Operational Lifecycle Model

An understanding of how building information modelling can contribute beyond the construction phase. Alternatives to the IFC schema, retrospective BIM other interdisciplinary tools are discussed.

Chapter 5: Research Methodology and Design

This chapter will introduce the areas of examination within the research through a quantitative framework embodied as the Physical Asset Lifecycle Model (PALM).. The purpose of the chapter is to present an approach developed through insight gained during literature review chapters. The PALM framework and it visual and statistical modelling subcomponents are discussed during this chapter.

Chapter 6: Results

Describes the development of the final LCC model, which will have been derived from the UK-wide data collection on AHU subcomponents across 6 PFI Hospital Projects. The real data collection and the Monte Carlo Simulation applied to the CIBSE recommended lifecycles shall form four lifecycle cost modelling options. The options are:

- Option 1: The recommended approach
- Option 2: The conservative approach
- Option 3: The balanced approach
- Option 4: The optimistic approach

Chapter 7: PALM's Impact on Decision-Making

Discloses the results of interviews with the CEO, Business Development Director and Regional Director (responsible for the case study hospital) regarding the PALM tool impact on their decision-making ability.

Chapter 8: Discussion

Discusses the main contributions of the work being stated including its limitations, before moving on to suggestions as to how the UK PFI market and overseas markets could utilise the new tool and its underlying logic. The chapter will discuss limitations of the work and future developments should the project be conducted again.

Chapter 9: Concluding Remarks

Conclude and place the research within the context of current technology and industrial practices for lifecycle modelling and costing in the UK.

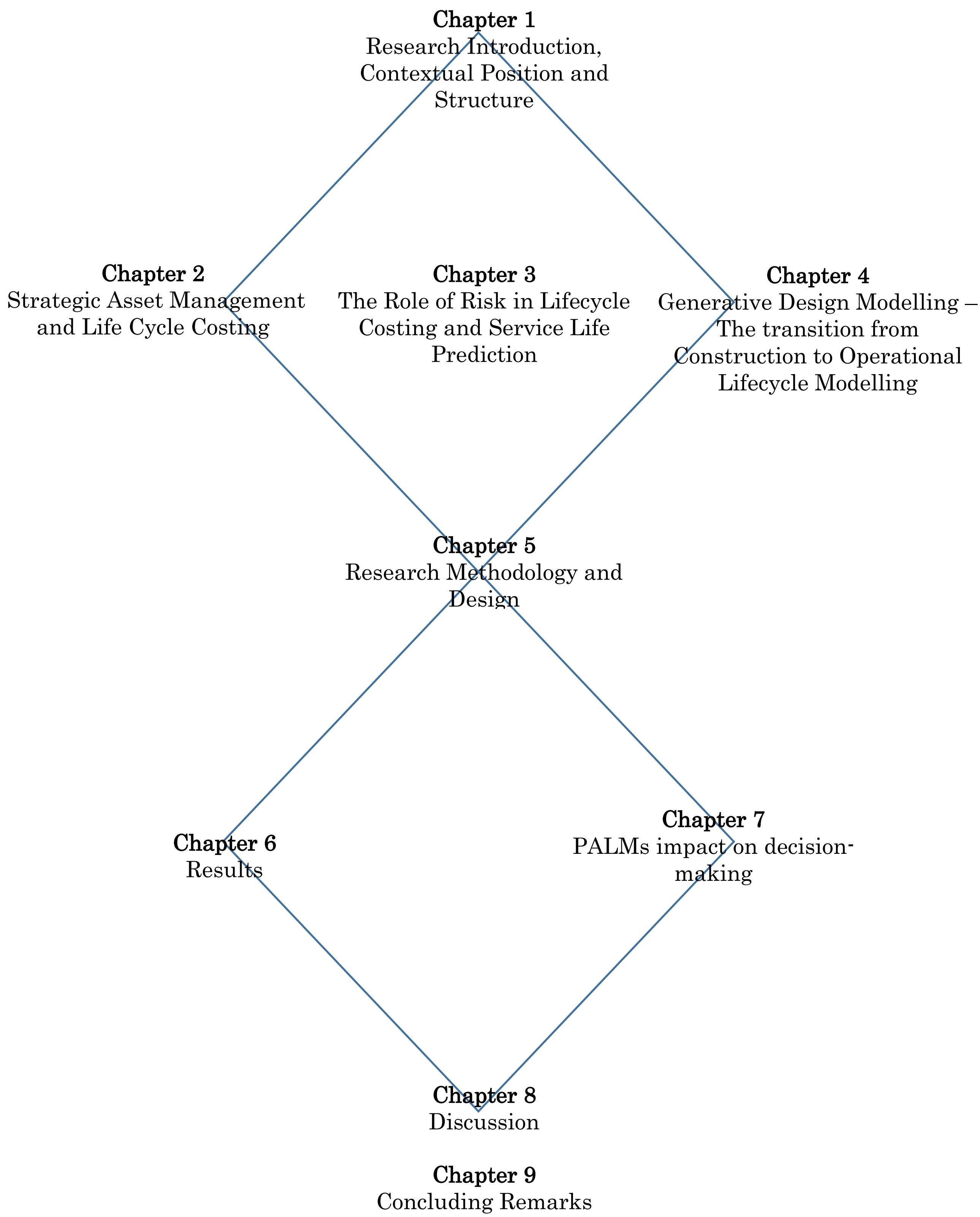


Figure 5: Research Information flow diagram (adapted from Design Council, 2012)

Chapter 2. Asset Management and Life Cycle Costing

2.1 Introduction

Strategic Asset Management (SAM) is an area largely unexplored because it is so finance-orientated and often requires an approach underpinned by fiscal, as opposed to research-based, drivers and logic. Over £25 billion of infrastructure re-investment is deemed to be required in the UK during the next 5-15 years (J. Woodhouse, 2011). With the current global economic recession leaving the UK with a debt level of circa £180 billion in the financial year 2013-14, it is unsurprising that there is already an awareness of good quality asset management, moving forward. In London, the underground system alone requires an estimated £35 billion of reinvestment over a thirty-year period (J. Woodhouse, 2009). This is a massive challenge in a time of ever-increasing technological and operational advancement and restrictive funding constraints. Evidence shows that up to 30% of the total cost of ownership can be avoided by better decision-making on what to do, and when (Woodhouse, 2011). The large sums of money involved in the management of company assets make this area one of critical business importance, spanning numerous industries. One of the more advanced pieces of industrial-based research is that of John Woodhouses' SALVO project. Introduced at the Institute of Asset Management (IAM) conference in 2010, the project is an international cross industry research and development project which seeks to establish best practice approaches to address key infrastructure asset management issues. It is an evolving process and has thus far yielded some innovative and flexible methods of evaluating life extension options and renewal timings (J. Woodhouse & Fiam, 2013).

2.2 What is Asset Management?

Publicly Available Specification (PAS) 55-1 defines AM as the 'systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their lifecycles for the purpose of achieving its organisational strategic plan' ((IAM), 2008). The terms 'systematic' and 'coordinated' refers to the time-based nature by which like-for-like replacement or renewal activities take place over the course of an asset's life. The consistency and accuracy of asset activity timing is crucial and the terms 'optimally' and 'sustainably' (sustainably in this instance, relating to business and economic continuity, as opposed to environmental sustainability) hinge on the timely nature of the replacement interventions, and impacts on the organisational strategic plan. The organisational strategic plan is the upward feeding of information collected by AM based activities. It is defined under PAS 55-1 as the 'overall long-term plan for the organisation which is derived from, and embodies, its vision, mission, values, business policies, stakeholder requirements, objectives and the management of risks' (IAM, 2008). Until recently, the term AM was most commonly associated with financial AM (Lloyd, 2013). AM in this instance is concerned with managing and guiding investments for increased fiscal returns. At this level, it is the responsibility of managers to communicate its benefits up and down the organisational chain (Lloyd, 2013). AM is a discipline spanning every level of an organisation. On a macro level, strategic direction from senior management (on which the survival of a business depends) is derived from the micro-level information gathered on the condition of the assets. This in turn underpins the aforementioned business objectives and management of risks to ensure business resilience and continuity.

2.2.1 The Term 'Asset'

The term 'Asset' is something which is far from precise. Different organisations, bodies and departments have different understandings of the term. For example, the IAM in PAS 55 defines an Asset as: plant, machinery, property, buildings, vehicles and other items which have distinct value to the organisation (ISO, 2008). The Oxford dictionary definition states an asset as being an item of property owned by a person or company, regarded as having value and available to meet debts, commitments or legacies (Oxford Dictionary of English, 2014). The ISO 55001 definition of an asset is an item, thing or entity which has potential or actual value to an organisation (ISO, 2014). This definition is far looser than its PAS 55 predecessor and these three more common references to the term 'Asset' highlight the importance of the way the word is interpreted. If an organisation is in the business of managing assets then its definition of the term will underpin any subsequent strategy which is derived thereafter. In the context of this thesis, the term 'Asset' is defined as an item, thing or entity which has value and is owned by an SPV company to whom management services are provided for the purpose of ensuring ongoing business continuity and contractual compliance.

2.2.2 Asset Management and Capital Renewal

There are different levels at which assets can be identified and managed ranging from discrete equipment items or components to complex functional systems, networks, sites or diverse portfolios ((IAM), 2008). The levels which AM affect are recognised in the PAS 55 standard as illustrated below.

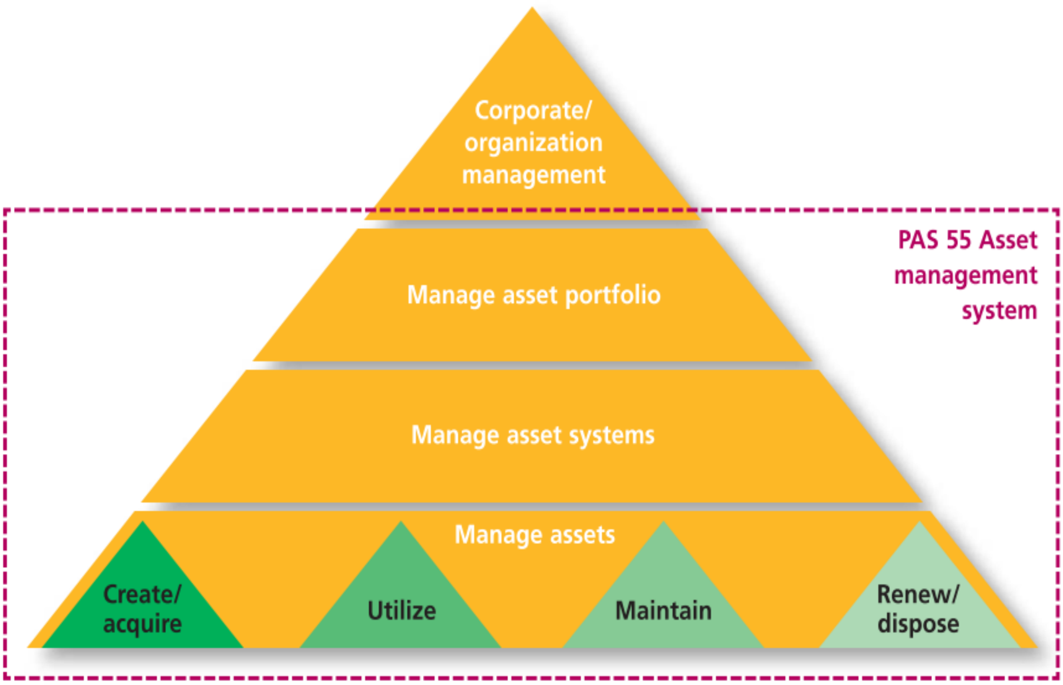


Figure 6: Asset management system levels (IAM, 2008)

From a capital renewal perspective, organisations and corporate management teams require only the most top-level information for making strategic decisions. Large businesses and institutions often have substantial infrastructures on which their economic activity is dependent. Aging facilities entail higher operational costs and concomitantly, render the business less attractive to discerning clients (Reindorp & Fu, 2011). Capital intensive industries beyond obvious sectors such as utilities and gas are now well aware of the long-term financial impact of aging facilities and are constantly looking for alternative ways to ease the slope down the Facilities Condition Index (FCI) scale. Such circumstances leave the asset owner with a choice – renew or replace? Burns argues that it is rarely either practical or desirable to replace an entire infrastructure (Burns, 1999). Reindorp concurs with that view, and that instead of capital replacement, problems must be addressed by replacement of subsystems (Reindorp & Fu, 2011). This approach is known as Capital Renewal (CR) and is essential in restoring economic value to physical infrastructures. Renewal decisions must balance future returns from infrastructure against future costs of renewal, but both of these are subject to some uncertainty (Reindorp & Fu, 2011). The space heating and ventilation system in HCP1 (comprising of 113 AHUs) has a foreseen expenditure of just over six million pounds.

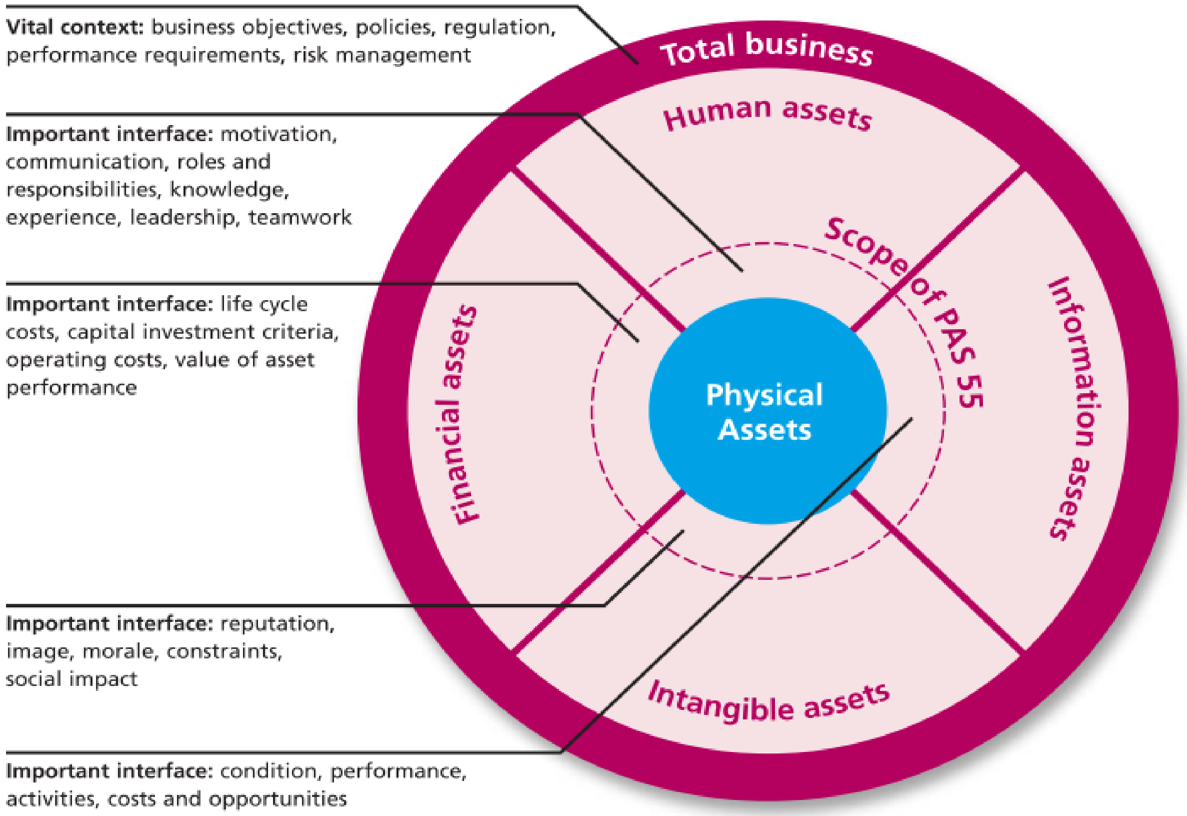
2.2.3 Asset Management Standards and Regulations

The rising costs of renewing or refurbishing ageing infrastructure assets, in some cases compounded by a lack of historical investment, meant that developing more transparent ways of justifying these costs became increasingly important for regulators (Lloyd 2013). It can be argued that the lack of historical investment has led to regulation becoming increasingly more involved in the management of physical assets. Until 2014, and with AM being a relatively youthful field, the three key pieces of legislation are recognised as being the Publicly Available Specification 55 (PAS 55-1 Specification for the Optimised Management of Physical Assets), PAS 55-2 (Guidelines for the Application of PAS 55-1) and the International Organisation for Standardisation 55000 (ISO 55000 – Overview, Principles and Terminology). ISO has recently released the newest suite of documents: ISO 55000, 55001 (Management Systems – Requirements) and 55002 (Management Systems-Guidelines for the Application of 55001). The BSI PAS 55 and resulting ISO 55000 standard for the optimised management of physical assets understands that AM organisations adhere to this structure and requires organisations to optimise their AM plans to three levels of granularity:

Table 3: ISO 55000 levels of granularity (descriptions adapted from Woodhouse, 2012)

1	The total activity programme, coordination and delivery of multiple activities across multiple assets (how do we optimally programme the conflicting urgencies of different activities to smooth resource requirements?)
2	Integrated optimisation of an asset's lifecycle management (what is the best combination of capital investment, utilisation, maintenance and life expectancy?)
3	Individual activities on individual assets (is this job worth doing, and if so, when?)

The key objective of every asset-geared organisation is to be able to successfully manage and operate its equipment to the fullest extent, thus maximising profit. Recapitalisation is a key theme and the notion of recapitalisation (the planned replacement of facility subsystems, such as roofs, utilities, heating ventilations and air conditioning) (Selman, 2003) is the overarching concept on which any legitimate AM strategy is based. Often the unit value of these combined facility subsystems (otherwise known as the facility replacement value) can amount to hundreds of £millions or £billions. But the questions remain, on what logic are these economic decisions made? How much knowledge of the operational process (granularity point three) do the decision-makers understand? And how is this information displayed? To answer these questions and understand how they can be improved upon, one must first understand the organisational structure and environment and the divide between those with influence, those with responsibility and those with neither. Until January 2014, the formal certification, guidance and recognition of sound AM practices was led by PAS 55 in combination with the IAM and incorporated the input of 49 organisations from 15 different industries in 10 different countries (Woodhouse, 2013). PAS 55, published in 2008 (2nd edition, 1st edition published in 2004)



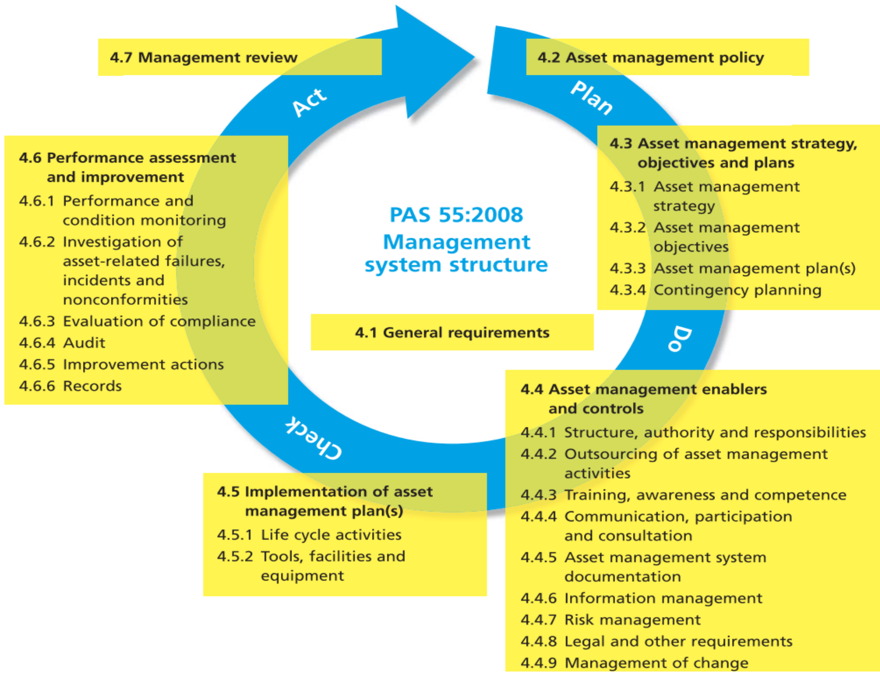


Figure 7: PAS 55 Scope (above) and Management system structure (below)

was widely adopted as the leading document around the globe. The PAS 55 scope is concerned with the management of physical assets (as opposed to intangible assets) and comprises a 28-point requirement specification with which PAS 55-2 provides guidance on the application. The specification defines what is to be done, but not how and, as such, allows companies to develop effective processes that reflect the challenges in their particular business (Lloyd, 2013). The format is based on the 'Plan, Do, Check and Act' cycle of continual improvement and is aligned with further standards such as ISO 14001:2007 (Environmental Management Systems) and OHSAS 18000:2007 (Occupational Health and Safety Management Systems). The document reflects the interdependent nature of AM and how each asset's inter-reliability extends beyond the physical assets and considers people, information, finance and other intangibles in its scope. The removal of 'silos' and the consideration of assets in systems, along with the cross-functional optimisation of their lifecycles, are core principles of sound AM (Woodhouse, 2013).

2.3 The Facility Condition Index

The FCI, introduced by Rush in 1991 (Rush, 1991) and published by the National Association of College and University Business Officers (NACUBO), is perhaps the best known and most widely used tool for capital planning and decision-making (Amekudzi and McNeil, 2008). The purpose of the FCI is:

- To assist in resource allocation decisions amongst the buildings in a portfolio, particularly with limited budgets which are inadequate in addressing the Deferred Maintenance (DM) in the facilities (i.e. priority identification).
- To determine the annual investment rates to prevent further build-up of DM.
- To help provide a KPI for resource allocation decision-making.
- A mechanism for monitoring changing conditions over time.
- A means to demonstrate the level of effort, due diligence and responsible stewardship to various stakeholders.

Its extensive acceptance was down to its ability to provide a relative benchmark to compare facilities without discriminating between size, usage, age and any other factor.

$$FCI = \frac{CD_{Fac}}{CRV_{Fac}}, \quad CD, CRV \geq 0$$

Equation 1: The Facility Condition Index Formula (Rush, 1991)

The FCI is defined as the ratio of estimated cost of remedying any Current Deficiencies (CD) in a facility to estimated Current Replacement Value (CRV) of the facility. It is a 'current' measure and its dimensionless nature permits comparisons and benchmarking across facilities or institutions (Reindorp & Fu, 2011). The formula for the FCI contains a numerator which is divided into a denominator to return a KPI in the form of a percentage with the numerator representing the catch up costs (also known as the renewal or DM costs) and the denominator representing the reproduction cost (also known as the replacement cost) of the facility in question. There are three general classes of reinvestment which are key in demonstrating the value of the FCI. These three classes are as follows:

While it has been accepted as the leading formula in facility benchmarking, the FCI does little from a capital renewal perspective because it is static in nature. Aside from benchmarking, the FCI does not provide explicit guidance on the problem of optimal renewal timing. A deteriorating FCI only indicates an increasing fraction of subsystems in need of replacement (Reindorp & Fu, 2011). While the FCI is a useful tool for providing investment defensibility at a given point in time, this leads one to ask the question as to whether the technique is fully adequate in dealing with long-term investment forecasting. The FCI is most frequently used as a KPI to objectively quantify the physical health of a facility in order to make two types of comparison on the relative condition of the facility in question: a comparison with other facilities in the same portfolio and a comparison against the same facility at some point in the past. The FCI is not an absolute statement of the size of the maintenance backlog of catch-up work, but provides an estimate for the purpose of decision-making. In accordance with the original formula developed in the 1990s, the relative measure of the condition of a facility is modelled into a four-tiered condition scale as follows:

Table 4: FCI Condition Scale

Condition	Value
Good	0-5%
Fair	5-10%
Poor	10-30%
Critical	30+%

The terms ‘good’, ‘fair’, ‘poor’ and ‘critical’ are linguistic references to describe the numerical value of the category which best summarises the facility’s current condition. The equation shown in formula 1 gives a decimal figure between zero and one. Translated into a percentage, a lower percentage means there is less deferred maintenance and the condition of the facility is healthier. The FCI is usually derived from building surveyors’ opinions on the installed assets’ remaining lifetime spans, according to CIBSE: Guide M recommendations.

2.4 Alternatives to the FCI

The alternative formulas for determining capital expenditure can be classified into two classes: top-down formulas and bottom-up formulas. Similar to the FCI, the output models form part of the expenditure plan in the financial analysis and forecasting of an organisation. Since the mid-1950s, a number of different formulas/models have been developed in an effort to derive a reinvestment rate for major maintenance and renewal costs at different stages in the facility lifecycle.

Table 5: Alternative Models

Model	Description	Formula	Pros	Cons

The Building Valuation Model	A desktop method of estimating maintenance and renewal requirements as a function of the CRV. -	$Annual\ Maintenance\ (M\&R) = y\%\ x\ CRV$ where y is the building constant and CRV is the current replacement value. In this calculation the CRV is determined by the gross floor area multiplied by a rate for its facility type.	Easy to use and adjust and require minimal data.	Accuracy is poor and should only be used as a general approximation for a facility recapitalisation budget.
The Lifecycle Actuarial Model	Breaks the facility down into its various sub-systems in order to establish preventative maintenance or repair frequencies for each sub system.	$Annual\ Maintenance\ (M\&R) = \frac{2}{3}BV \times \frac{BA}{n}$ where *BV* is the current building value, *BA* is the building age and *n* is the age weighted constants	Dynamic, considering age weighted constants to provide up to date models.	Sub system level means that components specificity is ignored.
The Mathematical Parametric Model	Made up of quantifiable variables and is exemplified by the NACUBO model (1990). Based on the assumption that annual maintenance and renewal funding requirements can be estimated with a mathematical equation	$B_n = (B_{n-1})(1+I_n+D_n)+(V_n)(P_n)-F_n)$ where n is the year, *B* is the backlog, *I* is the inflation rate, *D* is the backlog deterioration rate, *P* is the plant deterioration rate, *G* is the plant growth rate and *F* is the planned funding.	Their ability to accept and eliminate differing variables allows for a more project-specific outcome.	Complex and ambiguous on how to establish variables such as the backlog deterioration rate.

2.5 Lifecycle Costing

A lack of engagement from the FM team at the construction stage can lead to a lack of planning, post-construction. Such a lack of engagement is because the FM team aren't necessary at construction completion and so haven't been employed at this point. In PFI, availability-based contracts which provide customers with the use of assets such as machines, ships, aircraft platforms, or subsystems like engines and avionics, are increasingly offered as an alternative to the purchase of an asset and separate support contracts (Settanni, Newnes, Thenent, Parry, & Goh, 2014). These contracts have a different type of lifecycle based on risk ownership. Lifecycle Costing's most important use is in product analysis where costs expected over the asset's lifespan are large relative to the purchase and installation costs (Korpi and Ala-Risku, 2008). LCC has its roots in defence procurement practices and has been extensively applied across several sectors (Brown, 1979; Korpi and Ala-Risku, 2008; Settanni, Newnes, Thenent, Parry, & Goh, 2014). LCC begins with identifying a long-life asset such as a building, aircraft or one of their constituent parts. With the asset acting as the focal point, a one-off appraisal of the disbursements associated with its acquisition and existence over a given time span is carried out (Dhillon, 2010).

The latest ISO 15686: Part 5 – Lifecycle Costing defines the term as the cost of an asset or its parts throughout its lifecycle while fulfilling the performance requirements. Lifecycle Costing is the methodology for systematic economic evaluation of lifecycle costs over a period of analysis, as defined in the agreed scope (ISO, 2008a).. The ISO standard also states that LCC can address a period of analysis which covers the entire lifecycle or selected stages or periods of interest thereof (ISO, 2008a). The following diagram shows the major cost headings of 'BS ISO 15686: 2008 Part 5 Life Cycle Costing - Buildings and constructed Assets - Service Life Planning' and 'PD 156865 Standardized Method of Life Cycle Costing for Construction Procurement (SMLCC)' :

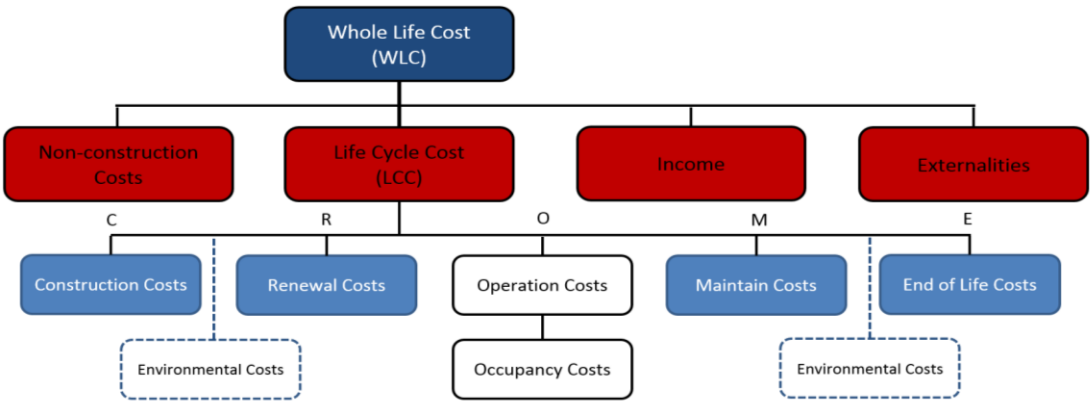


Figure 8: Whole-Life Cost, Lifecycle Cost (adapted from ISO 15686:2008)

2.5.1 Capital (Construction) Costs

The SMLCC defines capital costs as Costs payable for and in connection with the initial new building works and/or refurbishment works (ISO 15686: 2008). The capital costs are a one-time expense for the construction of the facility and are separate from the ongoing management of the facility, post-completion. In its simplest form, it is the total cost needed to bring a project to commercial and practical operation, inclusive of tangible goods such as the initial purchasing of plant and machinery.

2.5.2 Renewal Costs

The SMLCC defines renewal costs as the scheduled replacement and redecoration of major systems and components to form the detailed asset life cycle replacement cost programme. (ISO 15686: 2008).

2.5.3 Operational Costs

Previous NHS-based studies have included aspects such as cleaning, telecommunications, transport, laundry and portering costs (Kirkham, 2002). They relate to the 'soft' services involved in the running of the building (i.e. the costs associated with operations which are patient/client- oriented). SMLCC describes this cost as the cost incurred in running and managing the facility or built environment, including administration support services (ISO, 2008a).

2.5.4 Maintenance Costs

The SMLCC defines maintenance costs as scheduled and unscheduled maintenance a including planned preventative, corrective & inspection maintenance. (ISO 15686: 2008).

2.5.5 Acquisition Costs

Acquisition costs are defined as all the costs included in acquiring an asset through purchase/lease, excluding costs incurred during the occupation and use or end-of-life phases of the lifecycle of the constructed asset (ISO, 2008a). It is a broader description of the capital costs, inclusive of the land on which the facility is built.

2.5.6 Nominal, Real and Discounted Costs

The *Nominal Cost* is the expected price which will be paid in time, including estimated charges in price due to, for example, forecasted changes in inflation or deflation and technology (ISO, 2008a). The *Real Cost* is a cost expressed as a value at the base date of the model calculation including estimated charges in price due to forecasted changes in the efficiency and technology, but excluding general price inflation or deflation (ISO, 2008a). *Discounted Costs* are the costs resulting when a cost is discounted by the real discount rate or when the nominal cost is discounted by the nominal discount rate (ISO, 2008a). Discounting future costs (optionally coupled with inflation estimates) is an important decision-making component, heavily affecting the forecasted financial impacts of lifecycle.

2.5.7 Disposal Costs

Disposal Costs are the costs associated with the disposal of the asset at the end of its lifecycle, including taking account of any asset transfer obligations (ISO, 2008a). Asset transfer obligations in this instance could mean bringing the assets up to a predefined contractual position as set out in the PFI PA.

2.5.8 End of Life Costs

End of Life costs is the net cost or fee for disposing of an asset at the end of its service life or interest period, including costs from decommissioning, deconstruction and demolition of a building (ISO, 2008a).

2.5.9 The Discount Rate

As a rule of thumb, lower discount rates favour short-termism when assessing cash flow. This is because of the compounding nature of the calculation over time. As seems to be the case with many aspects of LCC, there appears to be a plethora of methodologies as to how the discount rate ought to be derived (Kirkham, 2002). However, given the very nature of PFI, it is arguable that the conventional methods of achieving the said figure are not appropriate. This is due to the way the contract is drawn up between the public and private parties. As discussed previously and shown in Figure 1, the unitary charge is split into three key components, one of which is lifecycle. The income stream can be deemed to be this figure in isolation (given that the nature of Lifecycle Costing either inadvertently affects the other margins of income, or perhaps not at all). So, the income payment for LCC is deemed to be a flat line. Based on the general notion that monetary value at present is worth more now than it will be in the future, the discount rate decided upon will have a huge impact on how 'steeply' the line descends downwards, particularly given the long timescales associated with PFI contracts.

2.6 New Rules of Measurement

The New Rules of Measurement (NRM) are produced by the RICS and provide a standard set of measurement rules for estimating, procuring and for the whole-life costing for construction projects. NRM3 is timely because the UK Government's Construction 2025 strategy has challenged the industry to find a way of reducing total whole-life costs by up to 33% (RICS Construction Journal, 2015). NRM3 is an important element of LCC because the adoption of a standard methodology facilitates consistency and benchmarking, thus aiding in avoiding disputes (designingbuildings.co.uk – accessed 20.04.15). The NRM suite consists of three volumes:

- NRM1 – Order of cost estimating and cost planning for capital building works
- NRM2 – Detailed measurement for building works
- NRM3 – Order of cost estimating and cost planning for building maintenance works

NRM1, published in January 2009, provides guidance on the quantification of building works for preparing cost estimates and cost plans. It also includes guidance on overheads, profit and inflation. NRM2, published in April 2012, came into effect on January 1st 2013 and replaced the Standard Method of Measurement 7 (SMM7). NRM2 establishes measurement rules pertaining to bills of quantities and schedules of works for obtaining tender prices. NRM3, published in March 2014, provides guidance on the quantification and description of maintenance works and can be used for the initial order of cost estimates, cost planning and most importantly, asset-specific cost plans. NRM3 also provides guidance on procurement and cost control as well as information on the measurement of other items associated with maintenance works. A reason for the recent adoption of the change has been described as facilitating greater cross-industry cooperation, the integration of BIM, and effective analysis of the costs of construction projects (RICS, 2015). NRM 3 has been described as ground breaking in a recent journal article and have been cited as having the capacity to significantly reduce whole-life costs during the key stages of a project (RICS Construction Journal, 2015). NRM3 has been produced following extensive collaboration with the Building Cost Information Service (BCIS), CIBSE and the Building & Engineering Services Association (B&ES), and the adoption of NRM3 has expanded cost structures thereby endorsing the Construction 2025 strategy. The Construction 2025 strategy places emphasis on pertaining greater cost certainty and transparency for minimising whole-life costs. Its BIM strategy requires whole-life cost information to be supplied at various stages during the project lifecycle. This means that the NRM3 elemental cost structure is now fully aligned with industry standard PPM task schedules (the SFG20 spec), and the economic reference life expectancy data structure published by the CIBSE Guide M and the BCIS cost analysis (RICS Construction Journal, 2015). Benefits in response to the Construction 2025 targets will be seen by improving Lifecycle Costing protocols. NRM will realise:

- Better informed decision-making
- Efficiencies and Lifecycle Cost savings
- Customer stimulation to procure and manage better
- Improved whole-life performance
- Evidence of whole-life performance, risk and cost benefits
- Robust cost analysis and benchmarks and BIM cost-data drops

The RICS article also makes specific reference to the PPP/PFI market. PPP/PFI projects are designed, built, operated and maintained and/or finance-based through lowest lifecycle costs and risks which fulfil the contractual and performance requirements. Looking at the PFI market and the more recent

BIM initiatives, it is clear that the industry urgently needs standardised approaches to predicting, assessing and reporting whole-life costings. The introduction of the new rules of measurement are envisaged to be a step in the right direction in terms of realising this goal (RICS, 2015).

2.7 Service Life Estimation

The Service Life of an asset and subcomponent impacts the WLC. This is also true in the PFI market, where cyclic replacement of assets coupled with fixed contractual end-dates means there is an impetus to ensure that replacements of high value assets do not occur at a point in time whereby there is no remaining time to recover the benefit through efficient service provision. Therefore, a view needs to be taken to establish when an asset will fail and require replacing.

Lair & Chevaliers (2002) research involved data fusion to establish plausible, probable, and believable rates of failure for an asset. Depending on the stance and risk appetite a decision-maker had, the variance in the predicted replacement of an asset can vary considerably. Lair and Chevalier's study considered two aspects in producing their results - modelling uncertainties and parameter uncertainties.

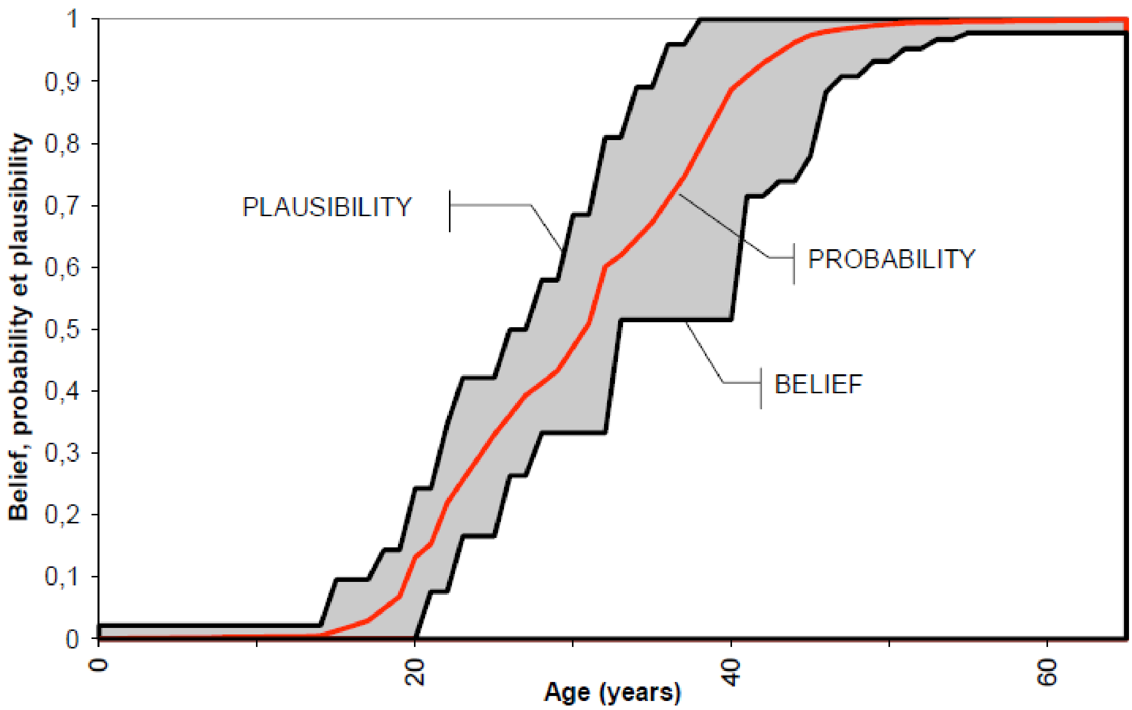


Figure 9: Failure distribution curve (Lair & Chevalier, 2002)

The international standard defines the period of analysis as the period of time over which lifecycle costs or whole-life costs are analysed (ISO, 2008a). The service life is the lifecycle from an engineering, asset-degradation perspective while the period of analysis looks at this from a commercial standpoint. A combination of both views is required for the development of an LCC model, and in the case of a PFI contract, both of these can be assumed to be the same.

2.7.1 Life Estimation Using IFPI's Risk-Based Lifecycle Proforma

A set of events can be graded depending on their likelihood and the impact of the occurrence (Ujjwal, 2011). Ujjwal cites three broad risk categories in this regard; occupational risks, societal risks, and financial risks. Risk-based lifecycle prediction has been published by International Facilities and Property Information (IFPI - Hurst, Williams, & Lay, 2005). The method presented by the IFPI enables members of the construction and FM team to contribute to the predictive process. The grey areas indicate the parts of the data collection exercise which the team can contribute towards, although it should be noted that the level of analysis in this instance is still limited to an asset system rather than the asset-component level. The objective of the technique is to demonstrate that an estimate of the 'normal' range of years between minimum and maximum life of a component or system is usually available from one source or another (Hurst et al., 2005). In PFI, the SPV subcontractors are usually privy to this information and are under no obligation to provide such data.

The factors which cause component failure before its natural end of life can be identified via professional experience using the proforma as the vehicle. The IFPI's proforma lists the most important of these 'Risk Exposure Factors'. The initial objective of the system is to get a consensus view from the project team as to the likely impact of each of these factors on the life of the asset under analysis (Hurst et al., 2005). The initial step in the process involves listing the normal life range, and in the example a pump with an expected lifespan of between 10-30 years respectively is used. This range is inserted into the 'life expectancy projection' box and the difference between the two is the maximum amount of life expectancy which the 'risk exposure factors' can influence (Hurst et al., 2005). Having established this 'range of influence', the team must next set about discussing the 'relative weighting' of each 'risk exposure factor' in a worst case scenario (Hurst et al., 2005). Here, professionals are being asked to prioritise based on their experience. If used in strategy-based decision-making, it establishes a clear link between strategic direction and operational delivery. In Hurst's example, the team will be asked to apportion the 'range of influence' between the four risk exposure centres, according to their view as to the seriousness of the factors regarding the early failure of the component in question (Hurst et al., 2005).

Project: Example Scenario - 1	Element: Component:	Heating installation Gas-fired boiler		Life expectancy projection		
				Maximum life-years Minimum life-years	30 (10)	30 -
Risk exposure centre	Risk exposure factor	Contribution to loss of life-years		Maximum loss	20*	
		Worst case	Probability %	Probable loss		
1. Component	Quality Manufacturer Obsolescence Complexity of operation	(8.0)	80	(6.4)		
2. Specification / Design detailing	Adjacent materials Adjacent detailing	(3.0)	90	(2.7)		
3. Installation	Complexity Site management Familiarity Competence Protection Accessibility Site conditions	(5.0)	70	(3.5)		
4. Local factors – in use	User activities Environment Location of Building Redundancy	(4.0)	35	(1.4)		
5. Others	Specify	-	-	-		
Maximum loss - years		(20*)	-	-		
* The ‘worst case’ total must always be the same as the ‘maximum loss’ prediction		Probable loss - years		(14.0)		
		Total predicted loss - years				(14)
Note: Tinted areas to be written by hand		Total predicted life-cycle - years				16

Figure 10: Risk appraisal lifecycle prediction pro forma, IFPI (Hurst et al., 2005)

The pump scenario is summarised as:

- Component -8
- Specification/detailing -3
- Installation -5
- Local factors -4
- Total = 20 years

The total must equal the life-expectancy range. The full range of views may be averaged out at this stage. Alternatively, the individual views may be pooled for statistical processing (Hurst et al., 2005).

The next step in the process is ‘scenario planning’. The instance described by Hughes et al. is concerned with the specific circumstances of the design, installation and use of the component.

Table 6: 'Worst case' scenario planning (adapted from Hughes et al., 2005)

	Potential Scenarios
Component	Is it a new or untried product? Yes
Specification/ detailing	Is it an inexperienced Architectural practice? Yes
Installation	Does the contractor have little expertise in the field? Yes
Local factors	Are there abnormal environmental conditions in the area? Yes

The example shown above is in the context of a new build, hence the architectural-based risk scenario. However, it is probable that the logic of scenario planning can be applied to the operation stage of a building’s lifespan, with foreseen scenarios being adjusted to suit the building lifecycle phase respectively. The next question is what is the ‘probability’ of the ‘worst case’ failure occurring given the scenario described? In the case of the view being presented in Hurst’s scenario, the probability forecast is a percentage likelihood: so the view is that 8 of the potential maximum 20 years lost could be down to component failure and that given the untried nature of the asset at the end of construction, there is an 80% chance that this worst case failure will occur. Others have suggested including different factors which might contribute to the failure of a part or component. For example, Ujjwal et al. found the following factors were key (Ujjwal, 2011):

- Current condition of the component
- Design life consumed
- Number of active damaged mechanisms
- Estimated rate of damage
- Efficiency of inspection
- Loading conditions
- Environmental conditions

Consequently, it was also found that the factors’ contribution to the instance of a failure included:

- Production loss
- Secondary damage (knock-on effects)
- Threat to personnel
- Rectification costs
- Impact on reputation
- Redundancy

If an approach is to include the appraisal of specialists' experience, the scope of these factors should be considered, too many may make a model unrealistic to maintain, too few may lead to inaccuracies.

An advantage of the IFPI method is that it allows uncounted factors in traditional lifecycle prediction methods to be examined. A second advantage is that the proforma is constructed in a clear way which can be rolled out across a project, making it a useful tool if data was to be collected from on-site operations teams.

A disadvantage is that service-life prediction on an annual time-step does not provide enough clarity on when the asset is likely to be replaced. A second disadvantage is that the approach takes a system-level stance rather than a system component-level stance. This will translate into financial 'allowances' for the system rather than specific components when the lifecycle funding model is produced.

2.7.2 Life Estimation Using the ISO 15686 Factor Method

The Factor Method is a way of obtaining an ESL of a component by modifying a remaining service life (RSL) through considering the difference between the object specific and the reference in-use conditions under which the RSL is valid. The differences are classified into seven factor categories as shown below the factor method is a way of grouping together agents or conditions which are likely to affect service life. The method enables assessment when reference in-use conditions do not fully match the anticipated in-use conditions. Its use can synthesise the experience of designers, observations, the intentions of managers, and manufacturers' assurances (BSI, 2008).

Table 7: The seven categories according to the factor method (ISO 15686:2008)

Factor	Factor Category	Description
A	Inherent performance level	Grade of component supplied
B	Design level	Components installation
C	Work execution	Level of skill involved in site work
D	Indoor environment	Exposure to indoor agents of degradation
E	Outdoor environment	Exposure to outdoor agents of degradation
F	Usage conditions	Effect of use of the asset
G	Maintenance level	Level of maintenance assumed

There have been a number of studies which have utilised the factor method in recent literature (Davies & Wyatt, 2004; Hallberg, Stojanović, & Akander, 2012; Marteinsson, 2003; Silva, de Brito, & Gaspar, 2012).

- Factor Category A: Inherent Performance Level - represents the grade of the component as supplied (BSI, 2008).

- Factor Category B: Design Level - reflects the component's installation in the building and is typically based on the level of shelter and protection from agents provided by the design of the building (BSI, 2008).
- Factor Category C: Work Execution Level - considers the level of skill in site work. It is based on whether the site work meets manufacturers' recommendations and is tightly controlled including overseeing issues such as asset storage, protection during installation, ease of installation, etc. (BSI, 2008).
- Factor Category D: Indoor Environment - considers the exposure of the asset to indoor agents of degradation and their severity. The general use of the building is taken into account, together with relevant local aspects. Indoor and outdoor environments are separated and for most components, only one such factor category applies (BSI, 2008).
- Factor Category E: Outdoor Environment - considers the exposure to outdoor agents of degradation and their severity. A meso-or local-level designation can be adequate (e.g. coastal, polluted) for this factor category (BSI, 2008).
- Factor Category F: Usage Conditions - reflects the effect of use of the building/constructed asset. The specific use of the space (where the component is installed) and assembly construction is likely to be relevant (i.e. communal spaces being subject to greater wear and tear). Activities present outside the building/asset can also be relevant (BSI, 2008).
- Factor Category G: Maintenance Level - reflects the level of maintenance assumed. For certain components which are accessible or require special equipment for access, a low maintenance level should be considered (BSI, 2008).

The Factor Method can be applied at different levels of sophistication, from a simple checklist to complex calculations. The level should be selected taking into account factors such as the purpose of the estimation, the quality of available data and models, the skill level and expertise of the users calculating the estimation and resources and time available for calculation (BSI, 2008).

ISO 15686 sets out four levels of sophistication, these are:

1. *Checklist Level*

The Checklist Level identifies the difference between the object specific and the reference in-use condition within each factor category. For example, an ESL equals 25 years ± 5 years, where ± 5 years is the confidence interval. The estimation of the confidence interval should be based both on the confidence of data used for the estimation of the value of the ESL and on the estimated inherent uncertainty in the procedure of estimating this value (BSI, 2008). This is the lowest level of the sophistication methods; and so requires the highest level of skill and experience of the user in order to obtain accurate service-life figures.

2. Multiplication Level

The multiplication level of estimation of the ESL should be conducted by multiplying the value of RSL by numerical factors A to G, each reflecting the relative dependence on the service life of the difference between the specific and reference in-use condition of the asset.

$$t_{ESL} = t_{RSL} \times \emptyset_A \times \emptyset_B \times \emptyset_C \times \emptyset_D \times \emptyset_E \times \emptyset_F \times \emptyset_G$$

Equation 2: Estimated service life formula

Numerous factors can be considered in the equation of ESL, but that not all may be necessary. For example, within an AHU, the external and internal environment regarding the fan motor may be important; however, this may not be the case with the attenuator. So this equation may be condensed:

$$t_{ESL} = t_{RSL} \times \emptyset_A \times \emptyset_B \times \emptyset_C \times \emptyset_D \times \emptyset_E \times \emptyset_F \times \emptyset_G$$

Equation 3: Estimated service life formula (environmental conditions ignored)

In this example, the indoor and outdoor environment is seen to have no implication on the in-use life of the asset, and so is removed from the calculation. It is up to the user to set or find the factor values of $\emptyset_A ... \emptyset_G$. The user can set factor values based on their degree of experience. Factor values are often based on known actions of the environment on specific materials or known effects of poor workmanship or maintenance. The user can find documented factor values of data enabling the calculation of these values. The method is based around the deviation of unity (1) from the observed RSL. A numerical factor can have a value between 0 and infinity, but should realistically have values close to unity. Preferably all factors should be between 0.8 to 1.2 (BSI, 2008).

3. Function Level

The Function Level states that the estimation of the ESL should be conducted by multiplying the value of RSL by an appropriate function, theta, of variables a,b…g, each of which reflects a dependence on the service life of the difference between object specific and reference in-use asset condition.

$$t_{ESL} = t_{RSL} \times \emptyset(a, b, c, d, e, f, g)$$

Equation 4: Estimated service life formula (function level)

The Function Level is a generalisation of the multiplication level and the variables are a generalisation of the numerical factors.

4. Combined Level

> An ESL may be estimated by combing the multiplication and functional level for groups of different factor categories, in which case the value of RSL is multiplied by one or more functions and one or more factors (BSI, 2008).

The advantage of the factor method is that it allows the examination of key elements which are likely to contribute to variation in service life. It also provides documented consideration of the relative importance of each (which is something unlikely to change irrespective of time – i.e. if an AHU services an operating theatre, this statement is likely to be consistent throughout the life of a project and so aspects of the prediction method do not need to be systematically updated over time).

The method does not indicate the seriousness of the failures, but interpretation of the results can suggest components whose use is 'too risky' without either enhancing the specification or providing regular condition monitoring.

2.7.2.1 The Use of Data in the Factor Method

BSI states that a numerical description of the reference in-use factors should be given (BSI, 2008). However, this is not always possible due to data deficiencies. Where this occurs, ISO recommends that a qualitative grading of the in-use conditions (A, B, C, F and G) within that factor should be made. Any qualitative information provided should be valued and interpreted to correspond to one of the in-use condition grades, 1 to 5.

Table 8: Grades, descriptions and guidelines for grading in-use conditions of factor categories (BSI, 2008)

In-use condition grade	Description (level/effect)	Guideline
0	not available	Should never be applied for the factor category "inherent performance level"
1	very high/very mild	
2	high/mild	
3	normal	
4	low/severe	
5	very low/very	
NA	not applicable	Should not normally be applied. A case where it may be appropriate to designate the grade as 'NA' is under the factor category "maintenance level," when dealing with a structural element for which maintenance is not possible.

Regarding the factor categories indoor environment and outdoor environment (D and E respectively), the reference in-use conditions for whichever factor category is applicable, or both, should be quantified in terms of agent intensities (very high to very low or N/A). This characterises the reference in-use conditions of the environments which can cause degradation. For discrete values, ranges of such agent intensities or standardised classes corresponding to certain ranges of agent intensities may be applied (BSI, 2008).

2.7.3 Life Estimation Using Evidence Theory

Evidence theory is based on the assumption that the service life assessment of an in-service building component can be considered as a multi-scale problem which can be defined within a multi-dimensional discrete space, within a process which evolves over time (below (Talon, Boissier, & Lair, 2008)).

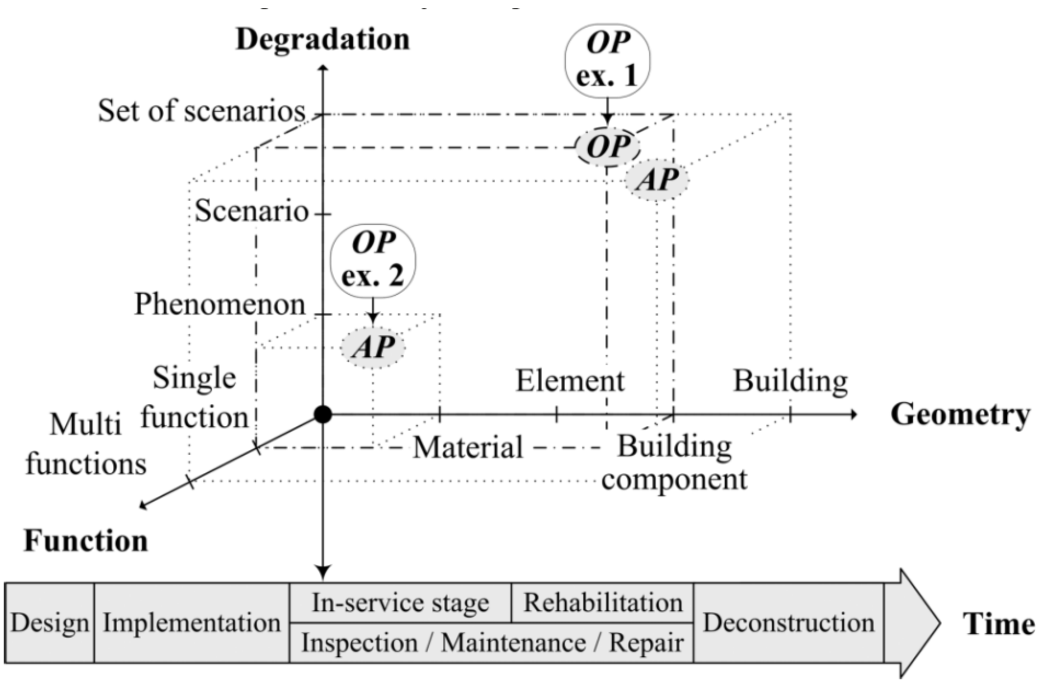


Figure 11: Service life assessment as a multi-scale problem (Talon et al., 2008)

Talons model deals with assessing the service life of in-service building components which are subject to known environmental conditions. The assessment is carried out within a multi-scale context: a geometric scale which ranges from the material or elemental to a building scale; a range in the complexity of the degradation (phenomena which varies from a single to various degradation scenarios); and, a range of possible performance requirements, from one function to several. Consideration is also given to the time in which the process is carried out which may span from the design to management and repair stages (Talon et al., 2008). The approach comprises four facets (represented on four axes):

- Axis 1 – Geometrical scale
    - Material level – PVC, concrete etc.
    - Element level – Steel beam, plastic tube etc.
    - Component level – Roof, wall etc.
    - Building level – A system of components
- Axis 2 – Aims and concerns of the user
    - Single function – environmental analysis, lifecycle replacement etc.

  - Multi-function – e.g. on a system level there may be acoustic, thermal and visual benchmarks
- Axis 3 – Degradation mechanisms influencing service life
  - Single phenomena – corrosion, time etc.
  - Single degradation scenario as a chain of several phenomena
  - Set of degradation scenarios containing those of the greatest critical nature with respect to duration, probability of occurrence, and gravity of consequences on the considered geometrical attribute and its environment (Talon et al., 2008).
- Axis 4 – The 3D 'user solutions' space
  - It may be considered during the design stage or during the in-service life of the building component, when some degradation has occurred and when, thereafter, degradation has come about (Talon et al., 2008).

The Objective Point is the point chosen by the user, where the service life of the building component being studied is to be assessed in the user-solutions space. The Assessment Point represents a point in the user solutions space which is a result of a fundamental study of the service life of the component or an accelerated short-term exposure test, feedback from practice, and expert opinion based on practical experience, a statistical model or some other such information which may provide an estimate of the service life of the component. (Talon et al., 2008).

2.7.4 FMEA and FMECA System Analysis

On identifying the system components, the parts which may require the greatest consideration need to be identified by more formal engineering analyses, such as Failure Mode Effect and Analysis (FMEA) and Failure Mode Effect and Criticality Analysis (FMECA). The former, FMEA, identifies the component failure modes and the impacts on the surrounding components and the system. The latter, FMECA, is an extension of FMEA in that it formally ranks components (either qualitatively or quantitatively) in terms of their relative failure criticality (Ujjwal, 2011). It is an analytical method for determining known equipment failures. It takes into account the design, manufacture and working life of parts to analyse likely failures.

2.8 Data Sources, Requirements and Methods for Estimating Asset Service Life

The term Reference Service Life can be defined as the service life of a component which is known to be expected under a particular set (i.e., a reference set) of in-use conditions and which may form the basis of estimating the service life under other in-use conditions (ISO, 2008b). The term Estimated Service Life can therefore be deemed to be the same as the term RSL, except where those in-use conditions are subject to deviation by RSL norms, following new data collection. It is generally necessary to determine ESL for an asset by modifying some form of RSL applicable to such a design object. Since the RSL is generated under conditions different from the in-use conditions to which the design object is subjected, it is essential to provide as much information as possible on the conditions under which the RSL is generated.

2.8.1 Manufacturers' Data

Manufacturers of building and construction products can have in-house information concerning the service life and durability of their products. Occasionally, manufacturers' data is made public in a product's declarations, or databases (BSI, 2008). The quality of this information varies and is often difficult to obtain because of the commercial implications of a manufacturer releasing its data, particularly with regard to life expectancy and warrantee periods. CIBSE states that the contractual chain which includes many subcontractors is particularly vulnerable because it distances the manufacturers and installers from the client (CIBSE, 2008). In the case of PFIs, this is particularly burdensome, rendering manufacturers' data difficult to obtain.

2.8.2 Historical Data

Scattered empirical knowledge from previous experience and observations of similar constructions in similar in-use conditions should also be used (BSI, 2008). The international standard also notes that the vast amount of existing scattered-quality data constitutes an important source of information, especially if data generated on ISO 15686-2 is not available (BSI, 2008). The general historical data is not likely to be available in a good format, often containing unnecessary information or being hard copy only. On being assessed, it will either be formatted or discarded, depending on quality and completeness. ISO suggests that this formatted data should be employed as a database which can be added to in future, while similarly being used in a factor methodology for producing estimates for asset service lifetimes. Eventually, it is hoped that the process of selecting general data will become the process of selecting RSL data (see Figure 12). The normal route for selecting data is expected to be the selection of RSL data. However, initially it is necessary for many data users to resort to general data as the only available source of information (BSI, 2008). It is likely that due to the nature of PFIs, any databases developed (which will already be numerous) will be commercially sensitive and therefore not shared between organisations.

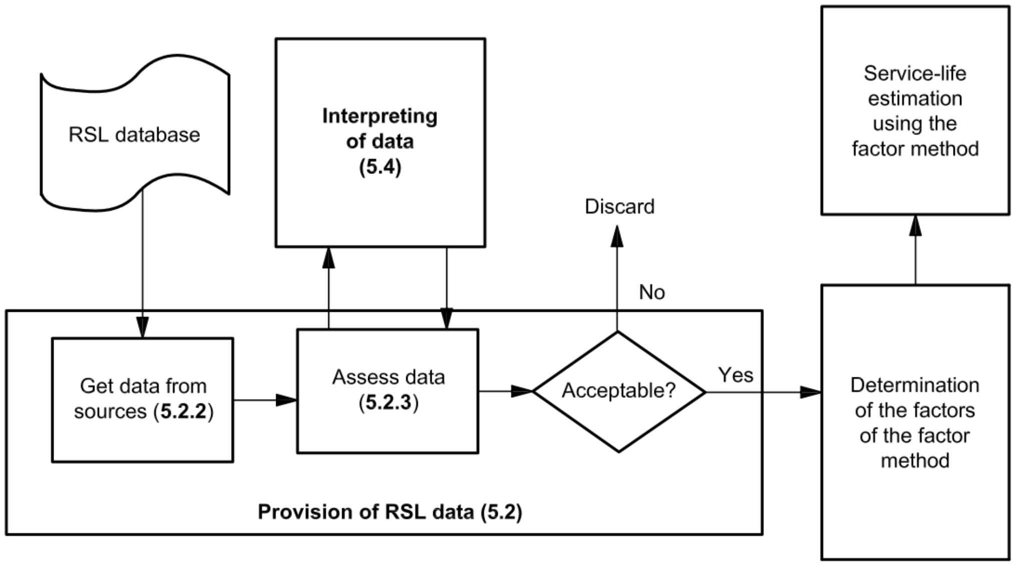


Figure 12: Process of selecting RSL data (BSI, 2008)

2.8.3 National Building Codes

National building codes list the typical service lives of components, and technical approval bodies can provide assessments of service lives in their certificates or reports of national product evaluation services (BSI, 2008).

2.8.4 Selection of Service Life data

ISO 15686:2008 stipulates that the selection of data depends on the intended end users, such as:

- Clients
- Owners and developers
- Professional advisors
- Constructors, suppliers
- Assessor and underwriters
- Managers of existing constructed assets
- Other users of such data

Service-life data should contain a general description of the material of components and data on service life in an indicated environment (Marteinsson, 2003).

Chapter Summary and Findings

- Lifecycle modelling in PFI makes no inclusion regarding the residual value of the building components or materials because they are fixed term contracts of between 25 and 30 years.
- The current model employed assumes expenditure of just over £6m for the 113 air handling units.
- The structure of the organisational context of this research is the management service provision of a number of 'silos', with silos in this instance being special purpose vehicles.
- Hard and Soft services within the building refer to replacement engineering and planned maintenance tasks.
- Stakeholders are demanding much greater transparency on how expenditure decisions are made, particularly concerning the assets worth investing in, exactly when and why.
- A tool which is used for strategic-capital planning should not provide too much commentary on operational aspects.
- The originality in this piece is from the understanding that at a time when competitive pressures forced asset managers to prioritise their maintenance, the risk-based methodology provides asset management with flexibility.

Chapter 3. The Role of Risk in Lifecycle Costing and Service Life Prediction

3.1 Introduction

The international standard on risk (ISO 31000) denotes the importance of ‘establishing the context’ as an activity at the start of the risk-management process. Establishing the context will capture the objectives of the organisation, the environment in which it pursues those objectives, its stakeholders and the diversity of the risk criteria (BSI ISO 31000, 2010). Risk affects all aspects of a business or organisation. So, the scope of risk management and assessment should be understood and aligned to the objectives of the organisation or the project in question. Lifecycle is where the key risks lie to a PFI management service provider. Controlling these risks will minimise the chance of project termination and maximise the chance of business continuity and stakeholder satisfaction.

PAS 55-1 incorporates risk in its definition of AM as being *the systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, and the risks and expenditure over their lifecycles, for the purposes of achieving its organisational strategic plan* (PAS, 2008). To a PFI contractor risk extends to having a deeper meaning than that of a regular in-house building maintenance team. While both face the operational risks one would expect with running a hospital, school or any other infrastructure, it is the funding route which separates the two. On top of statutory compliance issues, the SPVs need to ask themselves how much risk are we willing to take in running their assets? CIBSE is often used as the benchmark through which asset-replacement strategies are formulated. For the organisation to survive, exposing and controlling risks is essential (CIBSE, 2008). Organisations face internal and external factors which make it uncertain whether their objectives will be achieved. The effect this uncertainty has on an organisation’s objectives is coined as ‘risk’ (ISO 31000, 2010). With healthcare facilities reliance on HVAC equipment in combination with the ever-increasing application of technology, uncertainty looks set to stay.

Risk management is the identification, assessment and prioritisation of risks followed by the coordinated and economical application of resources to minimise, monitor and control the probability and/or impact of unfortunate events (ISO 31000). This takes an accepting and mitigating stance on risk and such an understanding has formed the basis for some interesting research approaches in the area (Bowden & Zhu, 2010; Conachey, Serratella, & Wang, 2008; Garber, Choudhary, & Soga, 2013; Mommers, 2014). For all but the most basic buildings, the built environment relies to a large extent on the building services engineering installations (CIBSE, 2008) This reliance on building services makes it an area of importance contractually and therefore financially. It is also an area of interest technically because often manufacturers' data on this equipment is not distributed on the grounds of commercial sensitivity, and so sound logic underpinning a risk-based replacement strategy for HVAC assets is a valuable commodity. Woodhouse noted that the business impact (in terms of risk and performances) of deferring expenditure or different projects is rarely quantified, yet is essential to demonstrate and manage systematically the different priorities for competing investment options (Woodhouse, 2012). Enlightened property owners are now beginning to formally address the risk potential associated with the operation of their building services (CIBSE, 2008). A recent study by Bowden and Zhu looked to establish a multi-scale approach to portfolio methodology which enabled better reconciliation between measurement and design methodology using multi-variance analysis (Bowden & Zhu, 2010). It was deduced that while the use of path risk was logical, the method was superior because the approach boasted flexibility through the use of user-definable preference weightings. The usefulness of user-definable preference ratings has been discussed in the previous chapter through the ISO 15686 ESL factor method.

From the day-to-day 'shop-floor' responsibilities to the hub of top-level business decision-making, risk is a term people appreciate yet it is a difficult concept to define. In quantifying risk we might wish to consider the ISO/ IEC guide definition (2009), namely, the combination of the probability of harm and the severity of that harm (ISO 31000, 2009). Risks affecting organisations can have consequences in terms of economic performance and professional reputation, as well as environmental, safety and societal outcomes. Therefore, managing risk effectively helps organisations to perform well in an environment full of uncertainty.

Risk can be considered to comprise two key components: variability (i.e. what is the variance in the potential outcome) and uncertainty (i.e. how sure can we be of each individual variable outcome). Variability, otherwise known as aleatory uncertainty or stochastic variability, is the effect of chance and is a function of the system, not reducible through further study or further measurement, but may be reduced by changing the physical system. Uncertainty, otherwise known as epistemic uncertainty or fundamental uncertainty, is the assessor's lack of knowledge about the parameters which characterise the physical system which is being modelled (Vose, 2008). The collection of knowledge or data which one may amass to construct a business case based on risk is one thing, but the financial interpretation based on the outcomes lies solely with the decision-maker. Taleb describes unpredictable events as 'black swans' and suggests that instead of trying to predict them in vain, we should adjust to their existence (Taleb, 2007). Where a system is life-critical or highly valued, there will always be a demand for the increased prediction precision of their useful life. It can be a route for minimising risk or allocating contingencies should undesirable events occur.

Risk can be defined quantitatively as the product of the consequences (C) of a specific event and the probability (P) over a period or frequency of its occurrence (Andrews, Moss, 2002).

$$R = C \, x \, P$$

Equation 5: Risk formula (Moss, 2002)

Probability or likelihood is the extent to which an event is likely to occur. It is a real number between 0 and 1, indicating the occurrence of a random event. It can be related to the long-run relative frequency of occurrence or to a degree of belief that the event will occur (Ujjwal, 2011). Risk probability can be defined on a 'degrees of belief' scale and can be expressed in rankings such as very low, low, medium, high and very high. Consequence is the outcome of the event. In the context of lifecycle replacement, consequences are always taken to be negative because the asset installed as new is used as the baseline. Decision-based metrics impact on the prediction of this event occurring, with consequence-criticality levels skewing the probability figure (and therefore replacement time) nearer and further away from the present day respectively, based on degrees of belief as to how the asset will perform over time.

Aside from being quantified, risk can also be visualised. Quantifying risk visually (Figure 13) can aid in stakeholder understanding of asset criticality and replacement timing. Below illustrates the concept of time-based risk, and the concept's ability to be visualised using a geometrical platform supported by a parametric computational engine. Most importantly, below displays how the colour gradient can be digitally distributed across an analogue scale through mapping (see Y axis). It also shows the concept of how the 'risk' gradient can be visually expressed dependent on the criticality of the asset and consequently how the parametric design will be able to 'step through' the colour gradient dependent on different levels of risk.

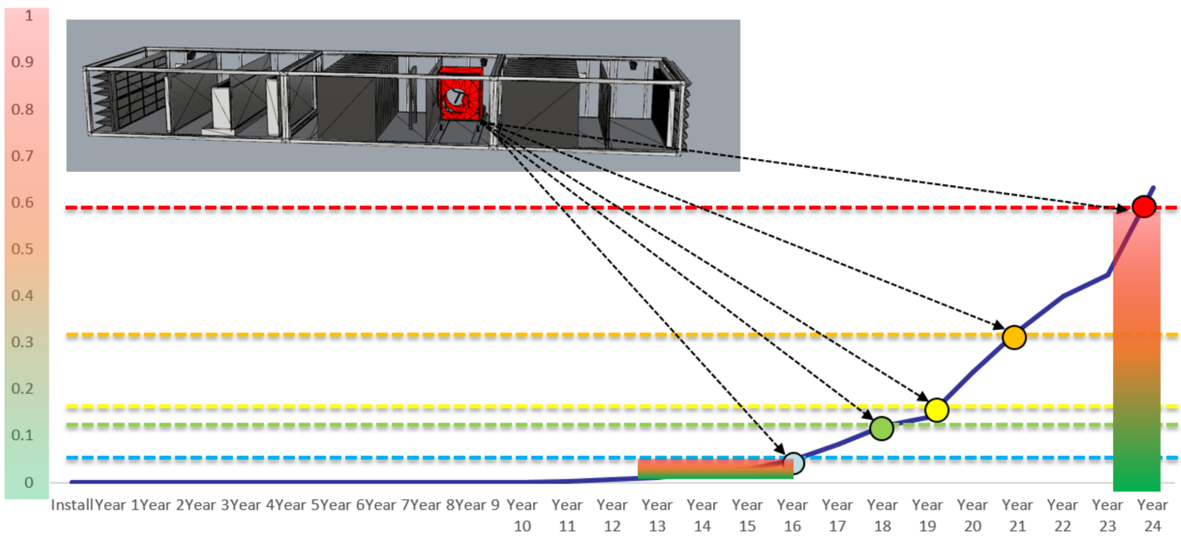


Figure 13: An example risk level visualisation of a supply fan component within an air-handling unit asset

3.2 CIBSE's Perspective on Risk

The Chartered Institution of Building Services Engineers (CIBSE) is the leading organisation for providing asset lifetime estimates for complex mechanical assets.

CIBSE is the benchmark and authority on building services engineering and forms much of the guidance on how long assets such as air handling units will last. It publishes guidance and codes which are internationally recognised as authoritative, and sets the criteria for best practice in the profession. The institution speaks for the profession and so is consulted by government on matters relating to construction, engineering and sustainability. It is represented in major bodies and organisations which govern construction and engineering occupations in the UK, Europe and worldwide. CIBSE is the key driver behind the current LCC modelling process in the UK's PFI market. According to CIBSE, risk can be classified into four generic categories:

- Business
- Design and Installations
- Operation and Maintenance
- Disposal

3.2.1 Business Risks

Business risks are related to the function carried out by the organisation and will influence the design of the building services from initial concept to final detail (CIBSE, 2008). Public sector clients (perhaps as a result of changing governments) are constantly adapting their buildings to suit new political protocols and agendas. From the point of view of the SPV, business risks relate to operational issues and from the MSP's point of view, they relate to safeguarding the contract which the SPV is contracted to run.

Organisations manage risk by identifying it, analysing it and then evaluating whether the risk should be modified by risk treatment in order to satisfy their risk criteria (BSI ISO 31000, 2010). The risk to life may be the highest priority in some of these examples, but all will include some measure of financial risk, either direct or consequential (CIBSE, 2008). In PFI, it is the risk of project closure (which may come about as a result of statutory non-compliance, financial deficit or any number of others reasons) and the intelligent management of assets will go a long way to ensuring this does not occur. Some components may be more critical than others to the overall risk to the business (CIBSE, 2008) but the question lies in how these risks are identified and how they are portrayed to the decision-makers.

The PFI contract is a subcategory of the PPP framework and is unique in the sense that it is extremely contractually geared. The client's performance-brief should state the parameters within which the building services will be expected to operate, taking into account both external and internal risks and the operation and maintenance regime necessary for the installation to continue and operate within the stated parameters (CIBSE, 2008). A typical PA contract will include many clauses for performance failures, making it a potential contender around which a risk-based approach can be based.

3.2.2 Asset Integrity Management and Dependency Models

Although the practise of risk management has been developed over time and within many sectors in order to meet diverse needs, the adoption of consistent processes within a comprehensive framework can help to ensure that risk is managed effectively, efficiently and coherently across an organisation (BSI ISO 31000, 2010). Asset Integrity Management (AIM) is a concept which incorporates risk management by default. Whilst a need for traditional approaches will always remain, it is increasingly felt that more advanced approaches are required to reflect the complexity and innovation involved in the assets, and to operate at an optimal level within the competitive pressures faced by asset managers (Ujjwal, Vadim, & John, 2012).

One of the principal benefits of optimised lifecycle asset management and concepts such as AIM is improved risk management as well as providing a clear audit trail for showing that the decisions taken and their associated risks have been properly analysed (PAS, 2008). Quite often, stakeholders will have individual agendas and will criticise any particular risk-based methodology, but it can be argued that given the number of stakeholders in such an environment, this is inevitable. A model which incorporates the entirety of the operational and strategic components within AM would be unwieldy and unmanageable because very few people have experience at both levels and the aptitude to manage and maintain such a model. Dependency modelling involves the logical mapping of risks, their source, and subsequent impact, should they be realised. This process maps the dependencies within an organisation and provides a visual tool to aid the prioritisation of resources to address key problems (CIBSE, 2008). The process mapping is complicated, including multiple goals and identifying multiple bottle-necks which often prove to be the ‘risk’ areas to business continuity.

3.2.3 Design and Installation Risk

The level of business risk directly influences the design and installation risk because it will determine the amount of investment required to design and install back-up or duplicate systems for the building services. The decision to provide standby plant and whether automatic changeover is necessary will arise from this (CIBSE, 2008).

3.2.4 Operational and Maintenance Risk

The management of operational risk is becoming increasingly important across all business sectors. Building managers will be well aware of the teething problems associated with the handover of new installations and the risks involved (CIBSE, 2008). A recent study conducted at Loughborough University in 2012 involved the optimisation of run-repair-replace design decision-making tools in the integrity management of assets with the ultimate aim of maximising the impact of money spent on mitigation actions (Ujjwal et al., 2012). Andrews and Moss (2002) define the term 'expected loss' (i.e. that which requires mitigation of some kind) as the product of Consequences (C) of a specific incident and the Probability (P) over a time period or frequency of its occurrence. It is with this basic understanding that the beginnings of a risk-based model can be developed. Development and implementation of appropriate operational risk-management controls, applicable to the buildings, facilities and resources which support the business, represents a significant challenge to an organisation. Management controls for business-critical environments need to address and evaluate four major elements: people, plant, processes and facilities, fully encompassing a range of hard and soft services (CIBSE, 2008). Figure 14 illustrates the main elements of operational risk.

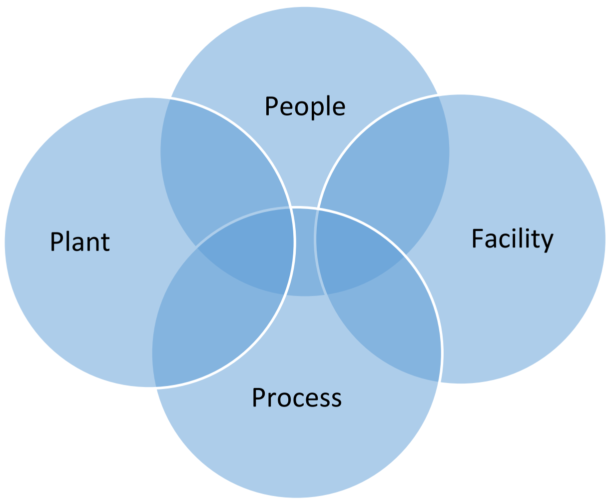


Figure 14: The four major elements of operational risk (CIBSE, 2008)

In order to demonstrate appropriate management and control, operational risks must first be identified. PFIs seek to allocate risks for design, funding, installation and operation to those best able to manage them, leaving the service user to get on with its business while service providers get on with theirs (CIBSE, 2008). Once identified, action can be taken to mitigate the risk or reduce the risk to an acceptable level (CIBSE, 2008). A combination of one or more equipment failures and/or human errors causes a loss of system function (Conachey et al., 2008). The maintenance programme will need to be developed from an assessment of statutory requirements, manufacturers' recommendations and operational risk (CIBSE, 2008). In large installations, maintenance during the defect liability period may be included as part of the contract for the installation contractor (CIBSE, 2008), thus avoiding any misunderstandings about responsibility should there be a failure within the component. Warranty and defect periods are also components influencing strategic-decision-making. Areas of high risk, such as high voltage or steam systems, require special operating and maintenance skills, procedures and training with the use of managed permit-to-work and access requirements (CIBSE, 2008). For example, evaporative cooling towers are particularly associated with the risk of Legionnaires disease, which can be controlled only within the framework of a formal and properly managed and audited programme of operation and maintenance (CIBSE TM13 - (CIBSE, 2008))..

It is necessary that an overall view of the client's business activities and reliance on supporting engineering and IT services be considered so that support-system interdependency and resilience can be fully understood (CIBSE, 2008). It is likely that many PFI contractual arrangements will include heavy financial levies as a result of HVAC-related performance failures. The impact to a client's business through the loss of a critical building or facility is a growing concern, and the loss of engineering services is the most likely and immediate cause (CIBSE, 2008). This is because engineering services provide the environmental conditions and 'dynamic' rather than 'static' aspects of operations. So criticality of AHUs and other HVAC assets becomes evident in highly complex facilities such as hospitals where the impact of non-compliant environmental conditions can act as a catalyst for the spread of illness and loss of business/reputational damage.

3.2.5 Plant Replacement Factors and Equipment Criticality

Equipment criticality can be graphed as a function over time. It is important to understand that equipment failures are not all the same. For most equipment failure modes, specific failure patterns are not known; fortunately, detailed knowledge is not needed to make maintenance decisions, thus supporting strategic-level AIM. Aspects of complex plant such as space allocation are seen as having a major influence on criticality. Allowing adequate space for maintenance and plant replacement is very important where the particular reference standard is in doubt, or plant and equipment have been 'shoe-horned' into a space, a variation factor should be applied (CIBSE, 2008). This is certainly a component which should be considered in any risk-based model. Take for instance a chiller which naturally receives cool-air intake from its sides and the output heat above. If the chiller was positioned in a tight room, the air intake would be restricted (possibly even inducing the output of its warmer air) and this would have an impact on its performance, potentially leading to early failure.

3.2.6 The Bathtub Curve

Future data is required for making predictions on asset failure. Conachey et al. (2008) define these characteristics as:

- Wear-in failure – known as 'burn in' or 'infant mortality' failure. Decreasing failure rate: this occurs when the system is new and is a consequence of teething problems such as design and installation errors, faulty components and manufacturing faults, amongst other issues.
- Random failure – dominated by chance failures caused by sudden stress, extreme conditions, random human errors, etc. during the 'useful life' of the component. Constant failure rate: in maintained systems, after the early failure period, the system will be in a settled state; random isolated faults and failures will occur, and parts which wear will need repair and/or replacement from time to time as part of preventative maintenance (Note: number and value of items could indicate its reliability). Such parts typically include bearings and heat-exchanger components.
-
- Wear-out failure – dominated by end-of-useful life issues for equipment. Increasing failure rate: this is the point where major components begin to fail and random failures increase with time. At this stage, the cost of repairs to the plant and equipment begins to exceed the cost of replacement.

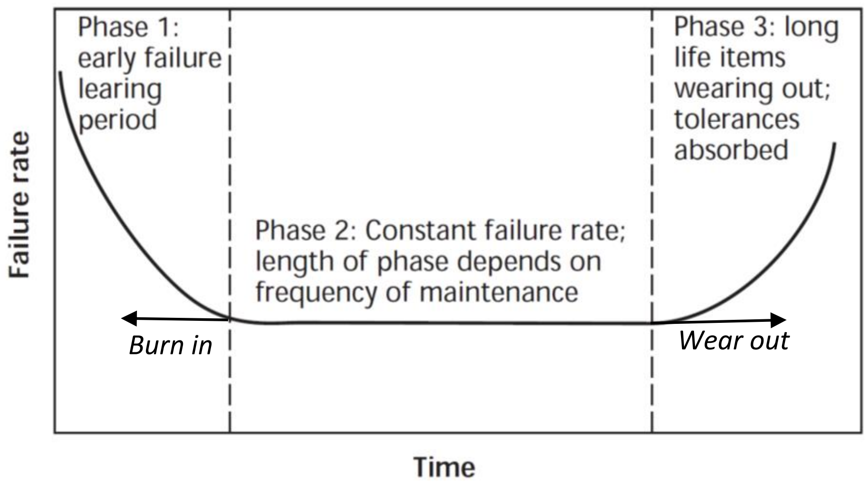
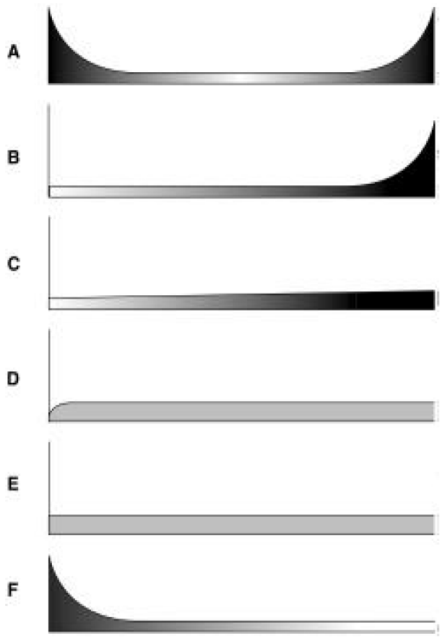


Figure 15: The Bathtub Curve (CIBSE, 2008)

These three failure characteristics are exhibited in the Bathtub curve. By identifying which of the three equipment-failure characteristics is representative of the equipment failure mode, we can determine the proper maintenance strategy (Conachey et al., 2008). The same deduction can be made in terms of determining backlog requirements against the recommended maintenance strategy and equipment-failure characteristics. When modelling backlog maintenance requirement costs in a lifecycle model, it can be hypothesised that the number of failure episodes in relation to the maintenance requirements (and actual maintenance carried out) could be used as a good indicator of the condition of an asset at a given point in time. The six categories for patterns of equipment criticality are shown below. These are:

- A – Bathtub Curve
- B – Traditional Wear-out
- C – Gradual rise with no distinctive wear out
- D – Initial Increase with a levelling off
- E – Random
- F – Infant mortality



A – Bathtub Curve

B – Traditional Wear-out

C – Gradual rise with no distinctive wear out

D – Initial Increase with a levelling off

E – Random

F – Infant mortality

Figure 16: Six patterns of equipment failure (SAE, 2002)

Economic life means the point in time at which it is less expensive to replace the asset than repair it (or its subcomponent parts). There are many other reasons why plant is replaced including the fact that it may be approaching the end of its technological or useful life (CIBSE, 2008). Retaining plant until it reaches the end of its economic life may not be the best engineering solution if it has already exceeded its technological and useful lifespan. The Bathtub curve is empirical and has been found to apply to composite products, systems or sub-systems with components which are subject to wear, such as rotating machinery (CIBSE, 2008). Systems include major plant such as chillers, air-handling units, heat pumps and lifts, etc. Therefore, by deduction, the 'useful life' can be interpreted as the period of time before the onset of increasing failure rates (the final phase).

3.2.7 Risk Assessment

Below illustrates a qualitative risk-assessment flow chart which is used in determining reliability targets in reliability centred maintenance (RCM) and reliability modelling.

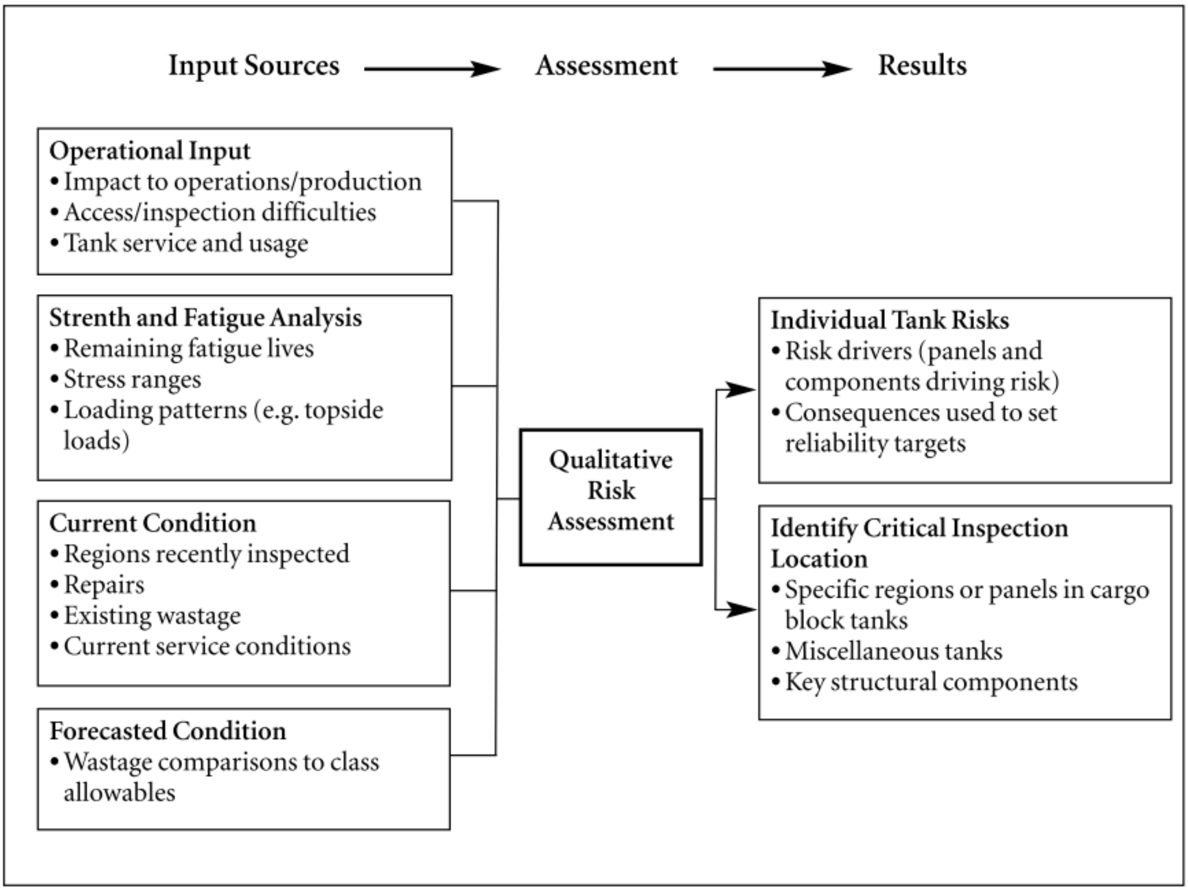


Figure 17: Qualitative risk assessment (Conachey et al., 2008)

In the instance of Conachey et al. (2008), such a system was adopted in the use of maintenance planning and asset degradation in ships. The maritime industry has been heavily involved in such techniques because of the nature of the risks involved in offshore transportation. Reliability Based Inspection (RBI) and the structural reliability-based methods arising can assist in providing a framework for quantifying loading and degradation mechanisms (such as fatigue), through systematically looking at the probabilistic uncertainty in each damage mechanism (Conachey et al., 2008).

3.2.8 The Damage Mechanism

A similar example was conducted more recently in the environmental sector. The degradation of wind tower structures was shown by identifying the key-damage mechanism (in this case, corrosion) which was monitored and graphed using the height of a recorded probability-density function.

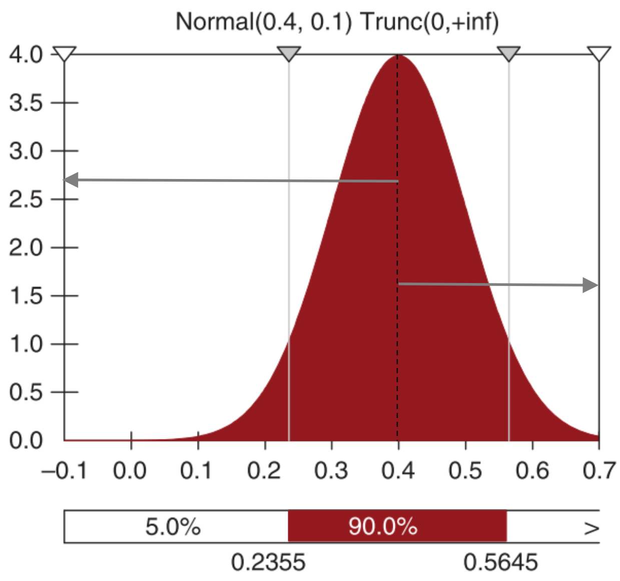


Figure 18: Corrosion rate (mm/year) distribution (adapted from Ujjwal et al., 2012)

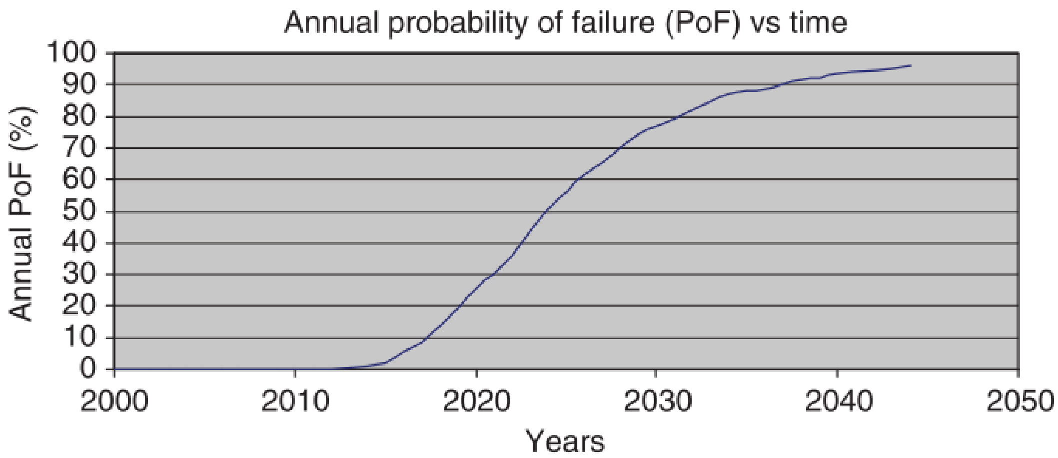


Figure 19: Annual probability of failure over time graph using the corrosion damage mechanism (Ujjwal et al., 2012)

It models the decline of an asset over time and probabilistic modelling is a good way of illustrating the degradation of an asset over time. One key drawback is the scope of the study. It fails to consider the 'criticality' of the asset in a set context. The corrosion damage mechanism is given to be 0.4mm because it forms the mean value in the entire distribution. The research is applicable and practicable because it provides a reasonable balance between operational information and strategic information. It does not discuss the details of damage models for use in probabilistic analysis. Instead, it illustrates a probabilistic damage-mechanism model for the general corrosion of the wind tower (Ujjwal et al., 2012) allowing the remaining life of the component to be calculated. The research is not transferable to other asset types which do not corrode or those assets for which corrosion is not their key damage-mechanism causing failure. This could lead to a lengthier and more bespoke data-maintenance and management process, should the technique be applied across an entire building – or in this instance – wind farm.

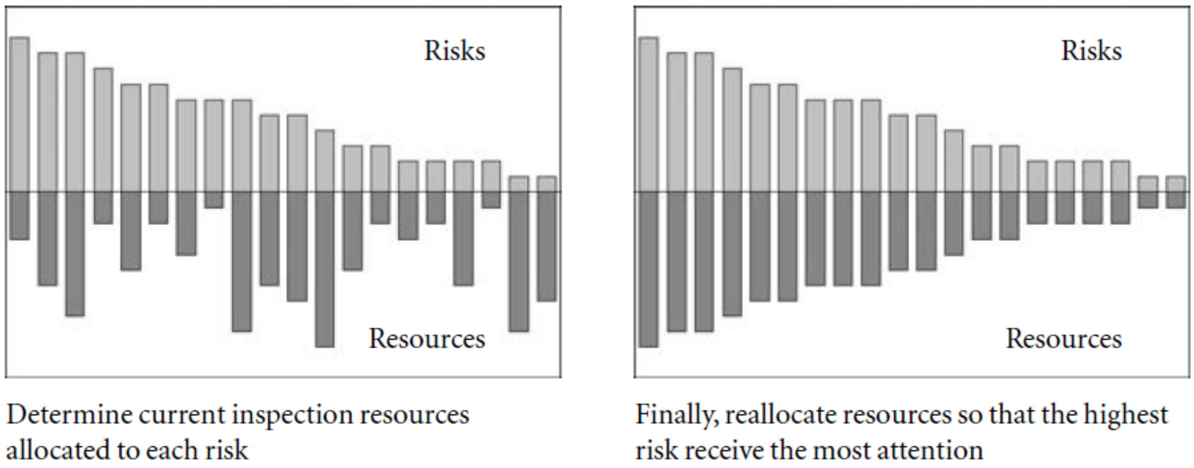


Figure 20: Risk and resource alignment according to risk based inspection (Conachey et al., 2008)

In Conachey's research, the logic missing from Ujjwal's paper is apparent because multiple resources and risk levels are considered. By applying and risk-assessment techniques to inspection planning, the operator is given a tool whereby he can justify the allocation of resources to those components with a higher-risk profile, and at the same time relax inspection activities for low-risk components to optimise and target inspection efforts (Conachey et al., 2008). The ultimate goal being that the resources are distributed to the area which has the most probable benefit for risk reduction.

3.3 Measuring and Estimating Asset Lifetime

The ability to measure and estimate lifecycle data accurately is crucial in assimilating a defensible business case to stakeholders. Ageing assets present some of the most challenging and critical issues facing asset managers. Despite the criticality and urgency of the situation, current decision-making practices are often subjective, inconsistent, and based on technical arguments rather than on robust 'business case' justifications (Woodhouse & Fiam, 2011). Accurately evaluating asset lifespans can have profound effects on the recapitalisation strategy of the organisation. The term recapitalisation has a nuanced definition. The one which is most commonly used throughout literature can be defined as *the planned replacement of facility sub-systems, such as roofs, utilities, heating, ventilation, and air conditioning* (Neve. T and Selman. J, 2002). Thus, recapitalisation is a process which relies on micro-scale detail (the asset sub-systems) under which macro-scale decisions (recapitalisation strategy and planning) are made. The benefits of a logical micro-oriented strategy can be huge at the organisational level, and evidence shows that up to 30% of total lifecycle costs can be avoided by better decision-making (T. Woodhouse, 2012).

The SALVO project found that major concerns are being expressed about ageing infrastructures across numerous sectors and the massive amount required in capital investment. However, Woodhouse still reiterates that decision-making methods in managing such ageing assets are still generally highly subjective and inconsistent, often based on short-term affordability rather than whole lifecycle cost/performance criteria (T. Woodhouse, 2012).

Risk, and whole-life cost-based decision-making is increasingly recognised as a key requirement for delivering and demonstrating value for money. There is a rapidly growing demand for skills and tools to assist in optimisation between conflicting business drivers: between capital and operating expenditures, between short and long-term impacts, and between costs, risks and performance (T. Woodhouse, 2012).

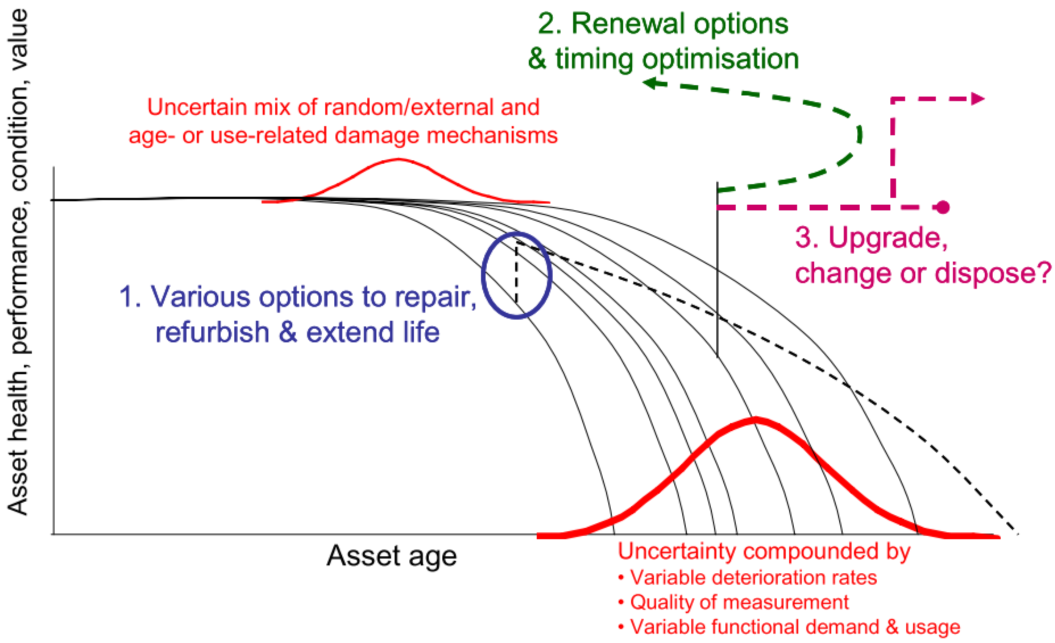


Figure 21: Example decision options faced with ageing assets (Woodhouse, 2012)

Above illustrates the uncertainty around an asset throughout an undefined period of time. The uncertain mix of random/external and age/use-related damage mechanisms means that no asset is ever the same, though its component parts may be identical. Varying deterioration rates, functional demand and the intermittent option to repair or upgrade at any given stage means that sound decision-making is key to ensuring availability and optimal asset performance. A key issue at this level of decision-making lies in the ability of a single tool to provide a lifecycle profile for a combination of different types of assets. This is because the stakeholders tasked with making such decisions are often limited in the amount of time in which to make a decision. Having one tool is a means of consolidating all the necessary information into one place, to enable more efficient decision making. In recent papers (Richardson, Kefford, & Hodkiewicz, 2013; Ujjwal, Vadim, & John, 2012), damage mechanisms as in the case of the corrosion of a wind turbine are described. The problem with this is that it cannot be scaled-up to apply to a facility because the level of detail is too granular. What about assets with components which do not corrode? Thus, for organisational strategy to be successful, it is essential to be able to create a single tool providing justifiable outputs across a multitude of assets.

3.3.1 Economic Life Factors and End of Economic Life

CIBSE defines an economic life factor as being an integral part of Lifecycle Costing and should be used when replacing plant items and components at intervals which, for the purpose of prediction, should be the economic life factors (CIBSE, 2008). For the purpose of prediction, a replacement forecast strategy based on a yearly profile is both manageable and defensible. The question must be asked as to what data these cycles comprise which will ultimately contribute to the financial model used to gain acceptance. CIBSE provides guideline estimates for HVAC equipment in terms of their replacement cycles, but stipulates that the information is only a guide. It is up to individual organisations to be able to formulate their own lifecycle profiles and edge away from the dependence on CIBSE.

Selman states that the useful lifespan of a typical industry-owned facility is about 30 years. However, most buildings are designed for 50 years, and most building subsystems have far shorter design lives (Selman, 2003). This explains the lengthy duration of contracts under the PFI scheme (up to 30 years or more), and the acceptance that the client naturally wants risk mitigation throughout the entire lifespan of the facility. A recent article by Presnak talks in detail about life extension of assets and how the benefits of a successful extension are real and quantifiable to the organisation. The underlying goal of life extension is to determine the technical and economic feasibility of continued plant operation while maintaining or improving availability, efficiency, operation and maintenance, and safety. When a decision is made to extend a unit’s service life, a systematic component evaluation can be used to select systems for evaluation, identify repair or replacement options, estimate the cost for the potential repairs and replacements and perform a cost benefit analysis (Presnak & Yee, 2014). CIBSE states that a system may comprise many plant items and components with various individual lifecycles, and this approach should ensure that a system operates at optimum performance (CIBSE, 2008). In too many of today’s new and retrofit projects, short-term thinking and a lack of rigorous financial assessment results in the irrevocable loss of opportunity for sound financial returns. Although not all high performance strategies have a financial basis, many that do are often overlooked (Roberts, 2014). WLC is a valuable technique which is used to assess the cost performance of constructed assets. It is used as a tool for identifying options where there are alternative means of achieving the client's objectives and where those alternatives differ not only in their initial costs but also in their subsequent operational and life-care costs (CIBSE, 2008). Whole-life costing in this instance is an approach to take when preparing a lifecycle profile because it can incorporate the long-term thinking and financial awareness needed to provide investors and stakeholders with a valid replacement strategy. CIBSE Guide M (Maintenance Engineering and Management) identifies the lifecycle phases of a system as being:

- Acquisition
- Use and Maintenance
- Renewal and Adaptation
- Disposal

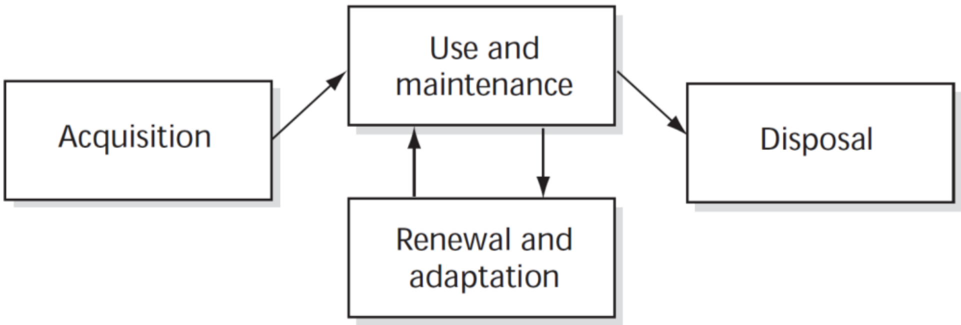


Figure 22: Phases in the life of a system (CIBSE, 2008)

The design life should be defined in the brief, and the estimated service life should be at least as long as the design life. Maintenance will be required for certain items to achieve the predicted/estimated lifespan. The estimation of service life takes account of the period during which the asset is intended to be used for its function or business purpose. This period will dictate the period of analysis of the WLCs and may dictate the design life for major assets and components (CIBSE, 2008). Kirk and Dell'Isola define the economic life, technological life, and useful life of an item as:

- Economic Life – the estimated number of years prior to the item outliving its economic life expectancy (the least expensive method of performing its function).
- Technological Life – the estimated number of years until new technologies render an item obsolete.
- Useful life – the estimated number of years during which an item will perform its function according to some established performance standard.

It is important that contractual and legal documentation clearly defines the basis of the life factors used to minimise misunderstanding and possible future disputes between the parties scheduled in the documentation (CIBSE, 2008). CIBSE states that their economic life factors are based on a good standard of maintenance and the hours of plant operation

Chapter Summary and Findings

- The ISO 15686 suite and standardised method for life cycle costing (SMLCC) provides the most well rounded and standardised method for structure a lifecycle model. However, these standards do not consider how data built in this way can be translated and represented in a visual model.
- The Bathtub curve dictates that typically mechanical equipment goes through a 'wear in' stage, where equipment failures are high, prior to finding operational stability.
- Risk-based inspection is something of an operational activity, currently there is no middle ground research within lifecycle costing that falls between simplicity and the justifiable outputs.
- Lifecycle models consider the ISO guidance with regards to service life data selection..

Chapter 4. Visual Modelling – the Transition from Construction to Operational Life Cycle Model

4.1 Introduction

Current post-construction studies on building information modelling (BIM) focus on transferring information from the design and construction phases to the operations phase by enabling, creating, and capturing digital facility information throughout the facility lifecycle (Akcamete et al., 2010). Currently available FM systems are not benefiting from the 3D visualisation capabilities that BIMs provide and the topological relationships between the components already available in them (Akcamete et al., 2010). This is largely down to the level of priority of BIM and FM in organisations. The impact of such modelling on asset intensive organisations' (such as the PFI industry) ability to manage PPM and lifecycle has potential.

4.1.1 Moving BIM into Operational Lifecycle Planning - the Concept's Key Benefits

Modelling asset information and visualising its output through parametric and generative design has produced a number of advantages for stakeholders; these include:

- Offering a new, alternative representation of asset management and investment planning data for all stakeholders.
- An improved grasp of proposed renewal timings of key assets for all stakeholders (particularly those stakeholders with little or no technical knowledge) through asset visualisation.
- Partnering with existing Strategic Asset Management reports
- Validating the work of industry professionals.
- Improving how corporate level capital expenditure planning is justified.
- Evaluating the validity and viability of proposed concession period replacement schedules.
- Component level replacement scheduling and viewing.

4.2 Building Information Modelling - the 'Wide' and the 'Narrow'

BIM is defined by international standards as the 'shared digital representation of physical and functional characteristics of any built object which forms a reliable basis for decisions' (ISO 29481-1, 2010).

BIM can be both narrow and broad-dimensioned. BIM in the narrow sense is modelled to fulfil specific required functionalities (e.g. maintenance (Hajian & Becerik-Gerber, 2010)); so when applied to existing buildings, the functionality-related level of detail (LoD) determines the technical specification of the data capture, processing and BIM-model creation (Volk et al., 2014). BIM in the narrower perspective, described as 'little bim' by Jernigan (2007), takes a focused view of the virtual model itself and its ability to act as a central repository for information related to the required tasks at hand (Donath, 2008; Eastman, 2011; Watson, 2011; Redmond et al., 2012) and its subsequent model creation issues (Cerovsek, 2011). A narrower BIM perspective has the benefits of providing functionality for a given task. This is useful in utilising the ISO 29481 standard definition of a BIM model, since the applications for such a tool can be vast and can contain unnecessary data.

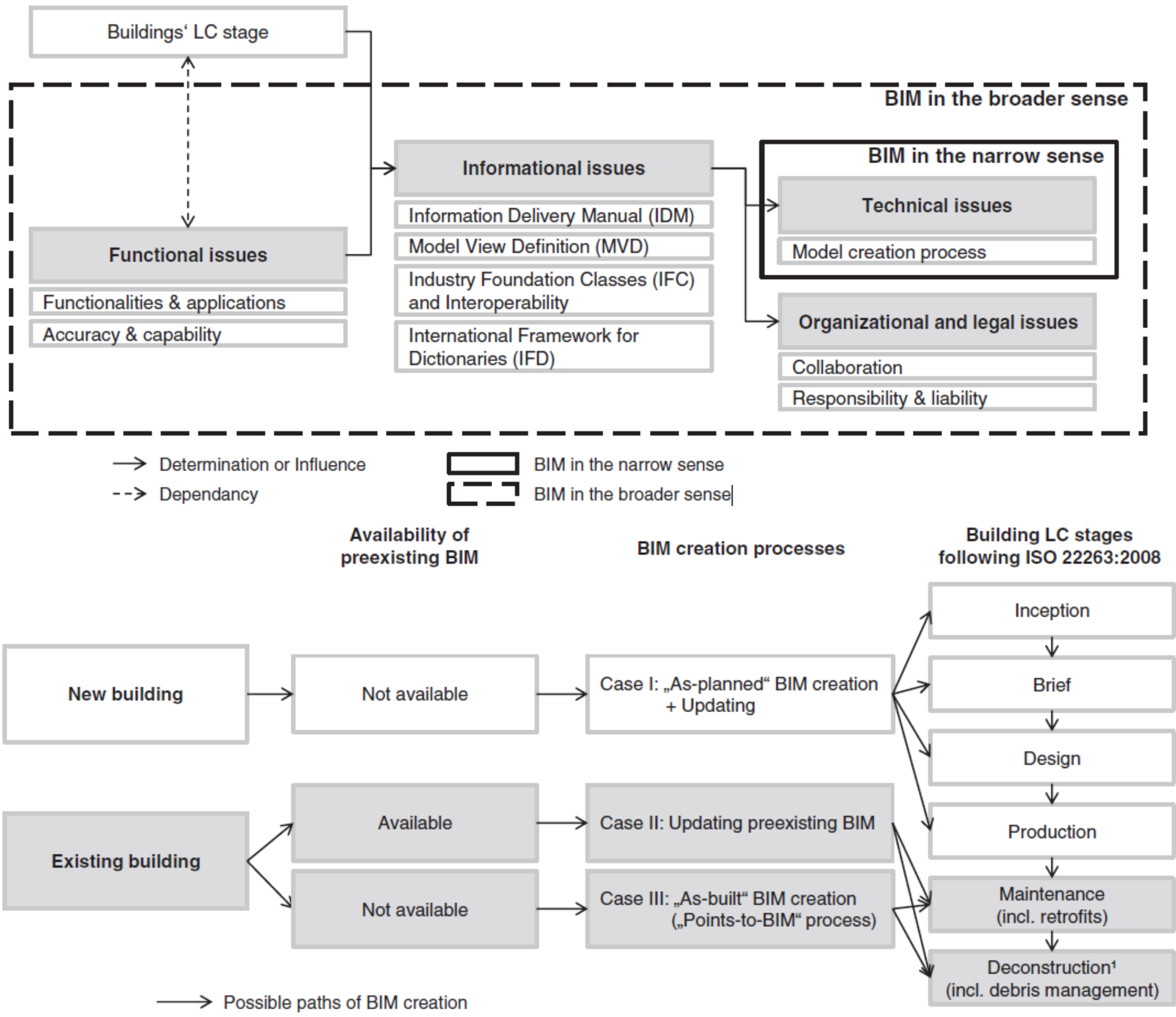


Figure 23: (above) Narrow and Large BIM scope and (below) New vs Existing building application (Volk et al., 2014)

The creation process of BIM models is different depending on where the building in question sits within its lifecycle. For new buildings, BIM is created in a process over several stages including the inception, brief, design and production stages (Case I). As BIM is not yet used by all AEC/FM stakeholders in the building lifecycle, some create isolated BIM solely for a designated, single purpose (Volk, Stengel, & Schultmann, 2014). Cases II and III in the lower diagram of the above diagram apply different design approaches. If the BIM model already exists, Case II suggests the existing model should be updated and adapted to fulfil the desired needs. Where the BIM model does not exist, an ‘as built’ BIM model should be created. More than 80% of all buildings in Europe were built before 1990 (Economidou et al., 2011), and the vast majority do not have building documentation in BIM format (Armesto, 2009). This leaves Case III as the only available option, and one which is rarely undertaken unless some financial or other benefit can be gained. If implemented, reverse engineering processes (‘points to BIM’) help in recapturing building information (Valero et al., 2011; Klein et al., 2012). The problem with this method is that retrospective BIM often does not capture information pertaining to components of complex assets which much of the PFI sector’s SPVs manage.

4.2.1 The Application of BIM in New and Existing Facilities

Depending on the project requirements, BIM application with architectural, structural and fabricational functionality is needed (Volk et al., 2014). It is possible that the entire building lifecycle could be modelled with the aid of BIM, but this often leads to diminishing returns as many of the phases in the building lifecycle pose risk to different parties. The specific functionalities of a potential model should be outlined prior to facility construction so that such an issue can be avoided. Functionalities are either inherent in 3D, 4D, or 5D BIM, or they are attached to BIM as independent expert applications. Expert functionalities use the underlying BIM data to support, extend, calculate or simulate specific business requirements. Results are either reintegrated into BIM or reported separately (Volk et al., 2014). Functionalities are based on process maps which describe the logical flow of information and activities as well as stakeholders’ roles within a particular functionality; (Redmond, 2012). Questions such as what the model shows, why the information is displayed in the way it is, and how this impacts on the business are all key questions which any model should take into consideration based on the specific requirements outlined prior to the design. According to a recent paper (Volk, Stengel, & Schultmann, 2014), BIM has been used in recent years for a variety of purposes, such as clash detection, construction progress tracking and quality control. Comparatively little explicit research has been conducted in the field of asset replacement and LCC visualisation. There are two reasons for this: the first being that asset-based visualisation tools would contain commercially sensitive information which a company may not wish to release. The second reason is that BIM is often used as a complementary tool, and in the context of AM and LCC there has been no link between an expert piece of strategic asset-management software and BIM itself. For new buildings, model creation of the ‘as planned’ BIM is done in an interactive, iterative process with commercial design or planning software and allows updating to ‘as-built’ BIM (Case I, Volk et al., 2014). ‘As planned’ BIM is a dynamic and forward facing process with updates included on an as-needed basis. The advantage of this is that the information level included in the model is lean. However, with the advent of 3D modelling technology being so recent, it has often been the case that the initial construction of a building has either pre-dated BIM or was an early adopter of it, and was therefore unable to afford and benefit from the latest technological advances on offer. Since many existing buildings have insufficient, pre-existing building documentation, either a pre-existing BIM is updated (Case II) or a 'points to BIM' process is performed (Case III) for grouping and modelling actual building conditions (below right part – Leite, 2011). There is a clear distinction between new and existing buildings. The three cases differ in their potential modelling effort. In most existing buildings, insufficient building information and no available pre-existing BIM leads to the Case III process being applied (Volk et al., 2014).

4.2.2 Operational Lifecycle Management within the Bew-Richards Ramp

The government has created stepping stones for the industry in setting the goal of Level 2 working by 2016 (Figure 24). Level 2 surmounts the difficult changes required to move into more integrated working. Leading practitioners are already working beyond Level 2 and early-adopter projects are in progress to test concepts which can move beyond Level 2 (Saxon, 2013). Level 3 (not currently within the scope of the government's 2016 plans) refers to iBIM. This will be cloud-based, and the software may be made available to users as a cloud-based service. This will remove the users' need for short-life, high-end work stations and fixed annual software costs: users would pay as they use it (Saxon, 2013). However, beyond iBIM lies an area which has been discussed in little detail. Existing building requirements, such as cause effect and deterioration modelling, (Asen & Motamendi, 2012) have not yet been considered. This is because, coupled with existing estate (beyond Level 3), a paradigm shift occurs where static skills needed for the construction phase modelling (i.e. clash detection) are replaced by dynamic skills (e.g. yearly visualisation of asset degradation). The future of BIM is significantly within the UK's potential to steer. It would be greatly to the UK's advantage to be proactive at government and business levels to exploit our potential as leaders in BIM (Saxon, 2013).

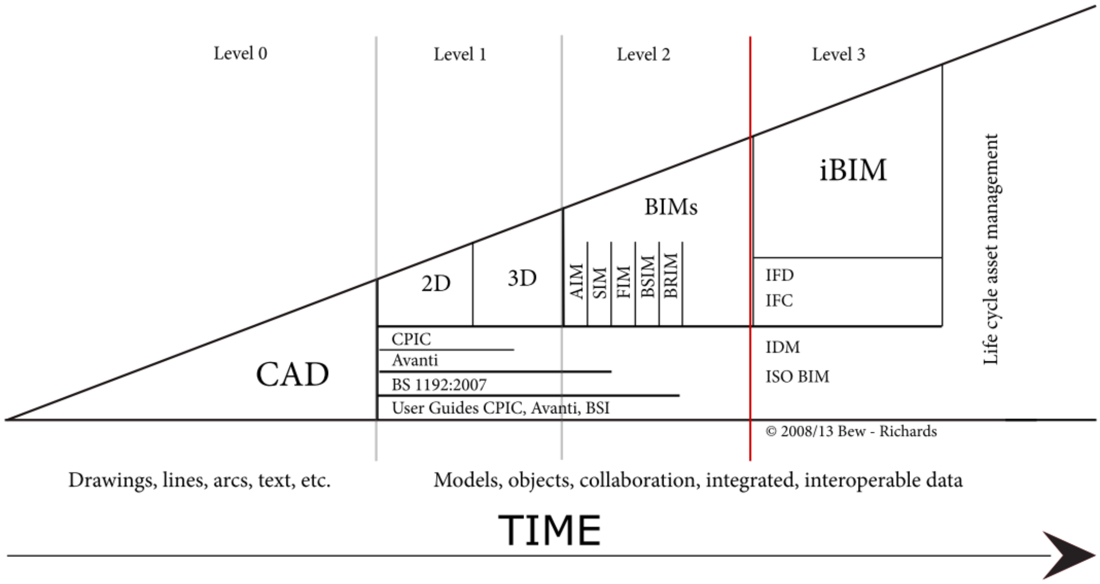


Figure 24: The Bew-Richards Ramp diagram (Saxon, 2013)

4.3 Reaching beyond iBIM - BIM Interoperability during the Operational Lifecycle stage

4.3.1 BIM in the Operational Life of a Facility

Throughout the lifecycle of a facility, the largest portion of expenditure occurs during the operational phase (Liu et al., 1994; Clayton 1999) and less than 15% of the total cost is incurred during design and construction. The longest phase of the lifecycle operations constitutes approximately 60% of the total cost (Teicholz, 2004). Reactive maintenance and replacement tasks can cost three to four times more than the same activity, if it were to be planned (Mobley, 2008; Sullivan et al., 2004). The opportunities for leveraging BIM for facility operations are compelling and yet utilisation of BIM during building operations is lagging behind BIM implementation for design and construction (Akcamete, Akinci, & Garrett, 2010), despite higher costs and seemingly higher wastage in the latter of the two lifecycle stages. Although the AEC industry started making some savings in the early stages of facility lifecycle, with faster delivery and change orders through usage of a virtual modelling and analysis approach, (Smith, 2007, Valentine and Zyskowski, 2009), there is an opportunity to net greater savings during the operations phase (Smith, 2007). Yet with such savings on offer, the industry seems reluctant to change, perhaps because around 90% of buildings do not currently have a BIM model to build upon and the cost associated with being a 'visionary' or 'early adopter' is perceived as too risky.

A study into the utilisation of BIM in the operations and maintenance lifecycle stage was conducted by Akcamete. He sought to use the tool for storing ongoing maintenance work orders to provide improved trend analysis of breakdowns in certain locations. The approach made use of the information in a BIM which is transferred from design and construction phases and leveraged the spatial relationships represented in a BIM for visualisation and analysis of facility data (Akcamete et al., 2010).

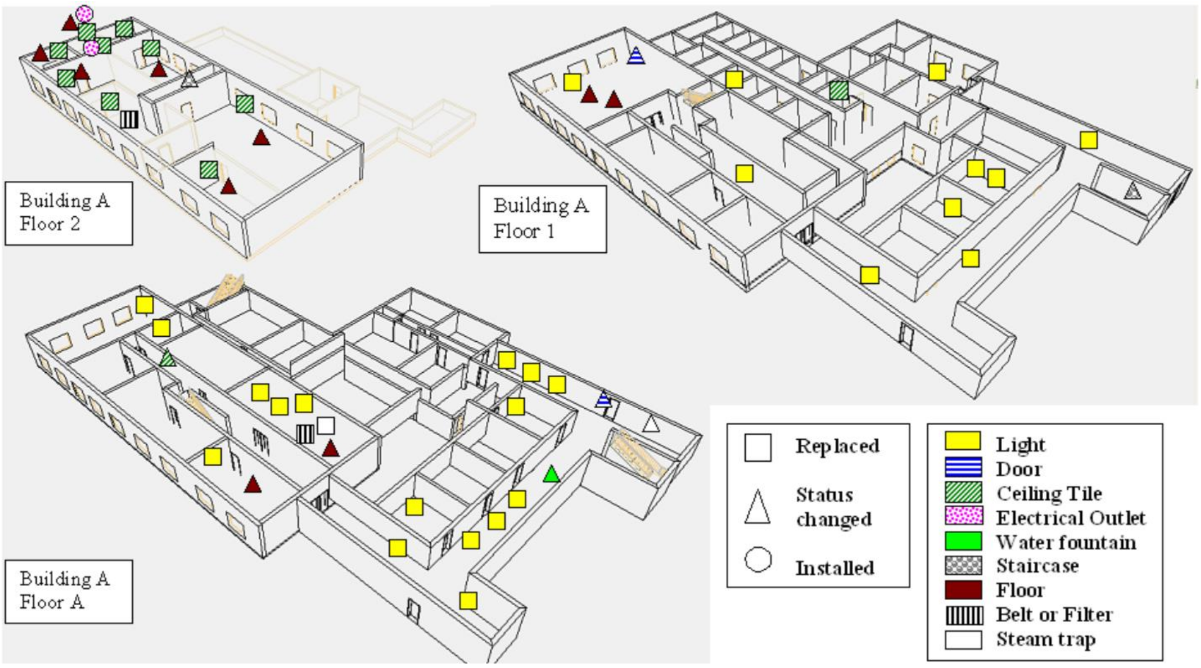


Figure 25: Maintenance and Repairs visualisation (Akcamete, Akinci, & Garrett, 2010)

As opposed to traditional data representation formats, BIM provides one model for storing all building information and hence enables integrated views (Akcamete et al., 2010). While the aesthetic output of the research is lacking in the necessary LoD, it begins to ask the necessary questions of the FM industry, namely, how can we utilise these existing BIM models for the long term benefit of our business?

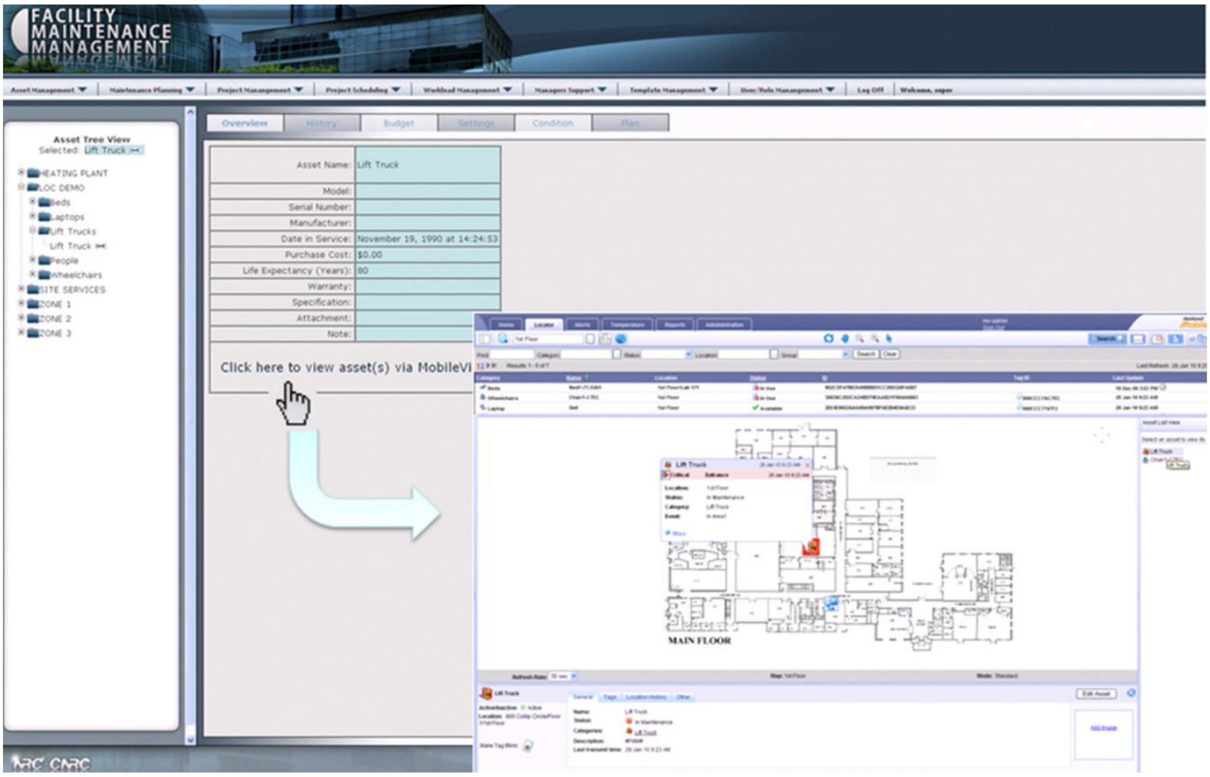


Figure 26: 2D location map for tracking assets (Shen, Hao, & Xue, 2012)

BIM provides 3D spatial information about a building and its systems, therefore it has the potential to support visualisation and spatial analyses of various maintenance activities happening in the facility. Such analyses might not be performed with traditional databases (Akcamete et al., 2010). Currently, asset management and lifecycle planning has almost zero crossover with BIM and 3D visualisation. While Akcamete's research used the geometry to illustrate maintenance activities, there is no foreseeable barrier as to why a model could not be designed for the use of lifecycle planning; existing lifecycle plans are available so it then becomes an exercise in designing the best way of visualising this existing plan. To shift away from the existing method of lifecycle planning, Klammt placed significant emphasis on the improvement in data collection which needs to take place. Daily FM operations need to be tracked to provide data for major repair and project-financial analyses (Klammt, 2001). Without the building performance and deterioration being fully documented, such decisions then need to be based on the personal knowledge base of the FM personnel (Akcamete et al., 2010).

Decisions on maintenance-related tasks are usually made based on various types of data, such as design drawings, inspection records, and sensing data (Bryde, 2013). Most of this data is text- based, which makes the process of correlating the information time-consuming and less intuitive (Motamedi, Hammad, & Asen, 2014). A paper published in the Automation in Construction Journal in 2012 set out to provide a decision-support tool for facilities management and maintenance and adopted a 'service oriented' approach for integrating data, information and knowledge captured during the facility lifecycle.

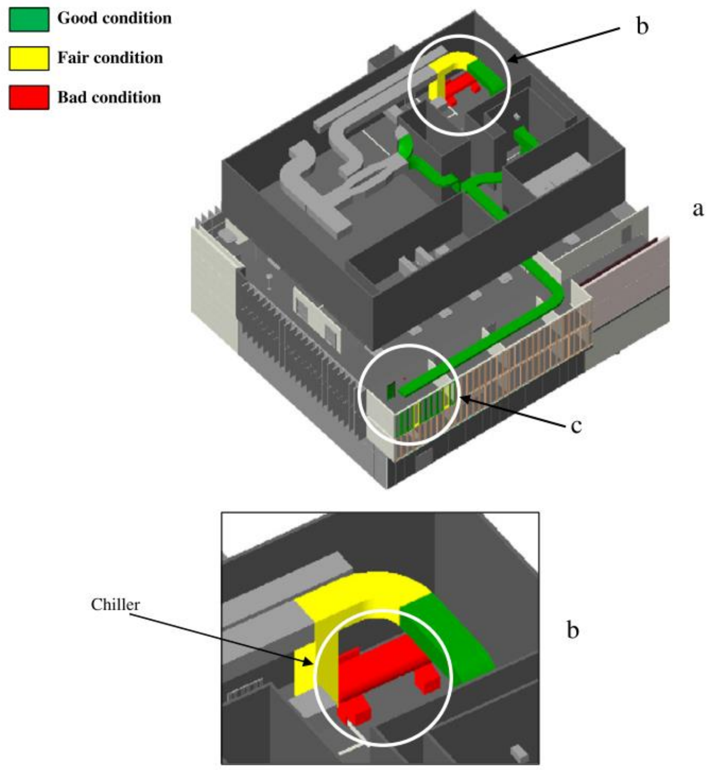


Figure 27: Visualisation of a Chiller query (Motamedi, 2014)

Above illustrates the output cloud-based model. The model utilised RFID technology to enable asset tracking and visualisation on the 2D floorplan. Shen (Shen, Hao, & Xue, 2012) stated that this was the most crucial contribution of his work and that it would be even more interesting to see BIM functioning as an information reaper for harvesting facility lifecycle information for use in FM. Shen's FM 2D mapping tool utilised technologies already past their infancy, and created a useful link between technology and AM for the purpose of ongoing maintenance and data collection (including heat and light sensors).

Above illustrates a recent study in visualising lifecycle works, and highlights the need for BIM 'catch up'. The results can be visualised to present the information (such as the condition of the assets), to be used for exploring the spatial distribution of failure root causes, and to infer failure patterns (Motamedi et al., 2014). The model is informative and employs the traffic light system, demonstrating the asset's condition. Knowledge assisted visualisation, which integrates and utilises domain knowledge to produce effective data visualisation, has been a fast growing field (Jernigan, 2007). Even in 2014, the LoD produced by such models is poor. In the instance shown in Motamedi's research, there is zero detail on chiller components and so this provides only limited data in terms of Lifecycle Costing, visualisation and planning.

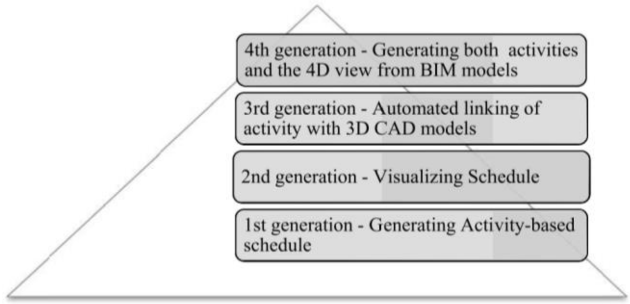


Figure 28: Evolution of Construction Schedule Generation and Visualisation (Kabir, Sadiq, & Tesfamariam, 2013)

Kabir's (Kabir, Sadiq, & Tesfamariam, 2013) evolution of the construction schedule generation diagram provides a diagrammatic representation for the level generation between activity scheduling and the visualisation of that schedule. The visualisation of lifecycle could prove to be invaluable in unlocking lifecycle capability and ensuring an MSP's trustworthiness for stakeholders. Visual analytics combines automated-analysis techniques with interactive visualisations for thorough comprehension, reasoning, and decision-making purposes on the basis of very large and complex data sets using the visual perception and analysis capabilities of the human user (Singh, 2011). This trustworthiness, facilitated through data visualisation, can transform clarity on organisational strategy, turning fund managers from static paper-based decision-makers with no intimate understanding of the specifics of what they are funding, into real-time decision-makers visualising their decisions in the board room.

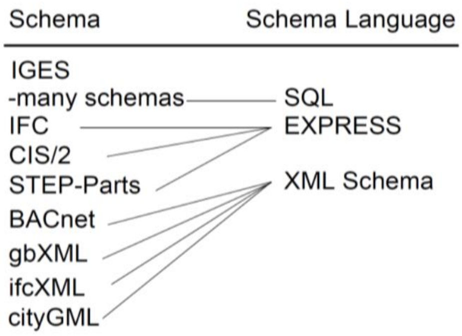
4.3.2 BIM Interoperability

'Interoperability' is the ability to exchange data between applications, which smooths workflows and sometimes facilitates their automation (Eastman et al., 2011). One of the key benefits of interoperability is the elimination of manual copying of data. Manual copying of partial data is an inaccurate process and can create inconsistency (Bazjanac, 2008). To eliminate manual copying (and remove human error as a result) a suitable data exchange schema must be determined.

4.3.2.1 Data Exchange Schema

ISO 16739:2013 specifies a conceptual data schema and an exchange file format for Building Information Model data. The conceptual schema is defined in EXPRESS data specification language. The standard exchange file format for exchanging and sharing data according to the conceptual schema is using the clear-text encoding of the exchange structure. Alternative exchange file formats can be used if they conform to the conceptual schema (ISO 16739: 2013). The document is designed for data sharing in the construction and FM industries and takes a positivist stance on the ability of both industries to progress in the area of data exchange. BIM data is exchanged across platforms in various formats (such as XML, CIMsteel (integration standard CIS/2 2007) and Industry Foundation Classes (IFC)). Each data-exchange process consists of the schema itself and the schema language, illustrated in the Table below.

Table 9: Schema and Schema Languages (Eastman et al., 2011)



4.3.2.2 Industry Foundation Classes

IFCs are open-data model specifications for defining building components' geometry and other properties in a way which enables CAD users to transfer design data between different software applications (Smith and Tardif, 2009). Is the IFC import standard something of an over-compensation for the purposes of the operational equivalent of 'narrow BIM'? As a major data exchange standard for BIM, the IFC standard is capable of restoring both geometric information and rich semantic information of building components to support lifecycle data sharing (Lin et al., 2013). Lin's method of utilising the IFC schema involved the planning of internal pathways within buildings. The method consisted of three main steps:

- Extracting geometric and semantic information
- Discretising and mapping the extracted information
- Finding the shortest path based on data mapping

Table 10: BIM Exchange Format Definitions (adapted from ISO 16739:2013)

Stage 1: BIM exchange format definitions that are required during the lifecycle phases of buildings	Stage 2: BIM exchange format definitions that are required by the various disciplines involved within the lifecycle phases	Stage 3: BIM exchange format definitions including:
• demonstrating the need • conception of need • outline feasibility • substantive feasibility study and outline financial authority • outline conceptual design • full conceptual design • coordinated design	• architecture • building service • structural engineering • procurement • construction planning • facility management • project management	• project structure • physical components • spatial components • analysis items • processes • resources • controls

• procurement and full financial authority • production information • construction • operation and maintenance	• client requirement management • building authority for permits and approval	• actors • context definition

Of these three stages, Stage 1 is deemed the only applicable step. The valuable geometric and semantic information is extracted from the input-IFC file, where the coordinates and attributes of the obstacles inside the building can be identified (Lin et al., 2013). The semantic information in this instance, while useful for other applications, will have little bearing on visualising lifecycle.

4.3.2.3 Barriers to the Extraction of IFC in Industry

A key barrier to the use of the IFC data schema in LCC is the lack of competent people who can demonstrate the modelling and data management skills. The IFC schema hierarchy is one which is complex (see below).

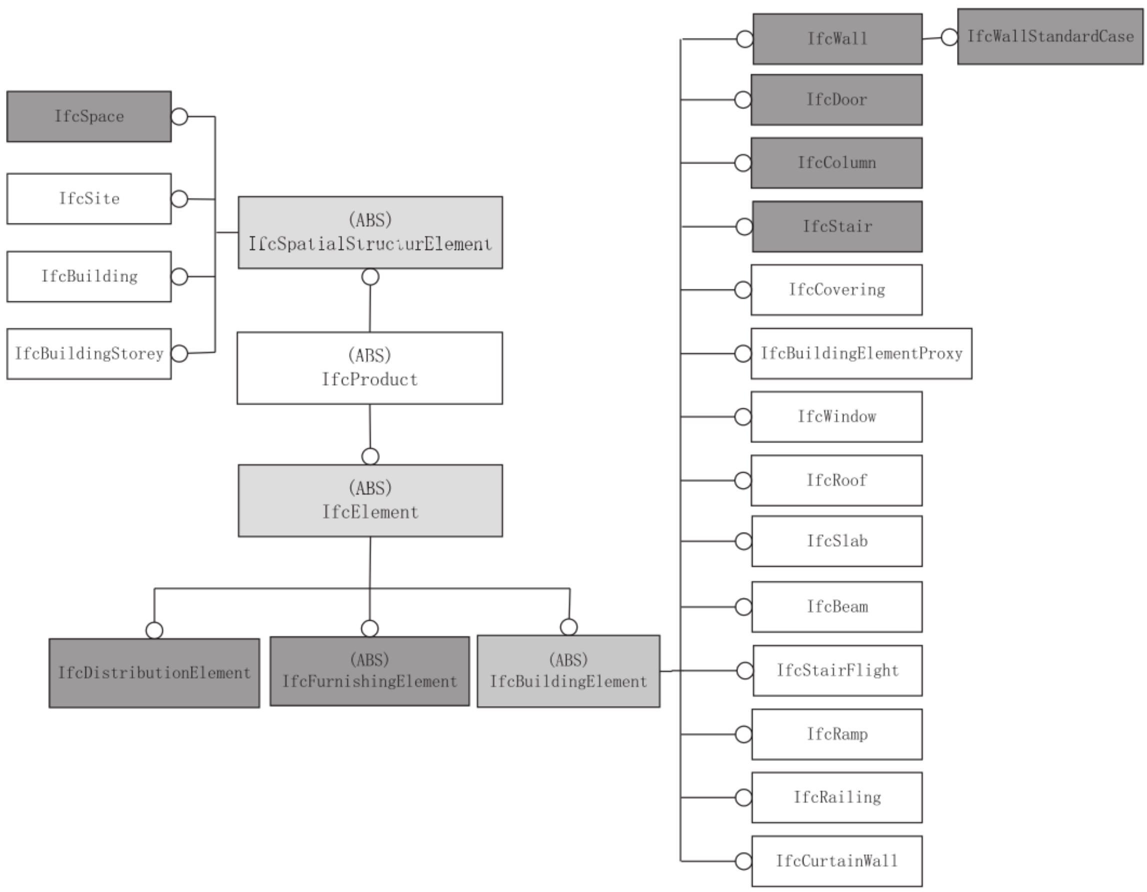


Figure 29: The hierarchy of the structure of part of the currently defined elements (Dalton & Parfitt, 2013)

The hierarchy of the schema is understandable from a construction point of view, because at this stage in the building lifecycle a number of AEC professionals are involved (architects, M&E engineers, façade subcontractors, etcetera). From a lifecycle point of view, different information is necessary. In a typical BIM model, the material is a necessity as the architect and client will want an idea of how the building will look. In lifecycle, the material of the component does not need to be visualised. In Lin's research there were over 300 supplementary data-types and property sets. Therefore, one would have to be certain as to what kind of information would be extracted from the input-IFC file (Lin et al., 2013). The hierarchy presented above defines elements within the IFC standard whereby all elements are inherited from the IfcProduct. One of the major drawbacks of IFC standardisation in LCC, is that it is difficult to extract specific information on the system and its sub-components and filter out items which are not relevant. For example, an IfcSpace (ward, office, and kitchen, etcetera) represents a volume of space enclosed by IfcWalls (walls), IfcDoors (doors) and IfcColumns (columns). Cleansing unnecessary data and converting it into inapplicable information consumes an asset management team's resources. While the geometrical information within an IFC is useful, it is unlikely that much of the semantic information will be utilised in LCC.

4.3.3 Alternative approaches

Alternative approaches to the IFC schema have been published (Sterling et al, 2015, Dalton & Parfitt, 2013). Modelica is a non-proprietary, object oriented modelling language (Sterling et al, 2015) that has been recently developed to run complex operational building simulation. An advantage of Modelica is the modularity of the language that allows modification of the code according to the specific needs of the application (Sterling et al, 2015). The object orientation enables the reuse of components, thus making the capture of multiple similar systems scalable and efficient. Some key offerings from such a scalable model were noted as being:

- Computational efficiency
- Accurate prediction of future states
- Cost effective

Using Modelica MPC relied on large computational resources and did not provide the support for the management of the uncertainty associated with the measured data in real time environments (Sterling et al, 2015). It was concluded that while the tool is expanding in growth (through the addition of new libraries and 'objects' from the open source community) it is important to note that the advantages of Modelica can turn against the unexperienced developer and that training of a user would be highly recommended (Sterling et al, 2015)

Another alternative to the IFC schema are workflows. A workflow is a data-formatting link between two independent pieces of software. A recent academic piece was aimed at documenting workflows which can be used to prepare large models for real-time immersive viewing through high-end display solutions (Dalton & Parfitt, 2013). As the construction sector begins its transition toward BIM, it asks the questions as to how feasible data-workflow interoperability is between differing software packages. Immersive visualisation facilities have been available for some time, new immersive facilities such as the Computer Automatic Virtual Environment (CAVE; Tutt and Harty, 2013) are starting to become more common. In terms of importing large models, seven challenges have been associated with workflows (Dalton & Parfitt, 2013). A complete definition of the workflows for the current leading software packages can be found in Appendix 1.

4.3.4 Exploring the 'Integrated' Market - a Leading Company offering a LCC-AIM Tool

Manhattan Atrium is the UK's leading supplier of Enterprise Asset Management (EAM) solutions. The Atrium EAM system addresses both strategic and operational needs of property asset and facilities management. It focuses on helping organisations reduce costs by adding value, managing risk, and improving performance through adopting better asset management practices. The software suite is made up of two main parts (www.atriumsoft.com/ accessed May 2015):

- Strategic Asset Investment Planning - enabling the organisation to measure past, present and future performance, and make evidence-based decisions to optimise the use and management of assets in line with long-term corporate objectives.
- Operational Asset Management - delivering efficiencies and a joined-up approach across a comprehensive range of functions, from surveys and maintenance, to helpdesk, contractor-management and KPI reports.

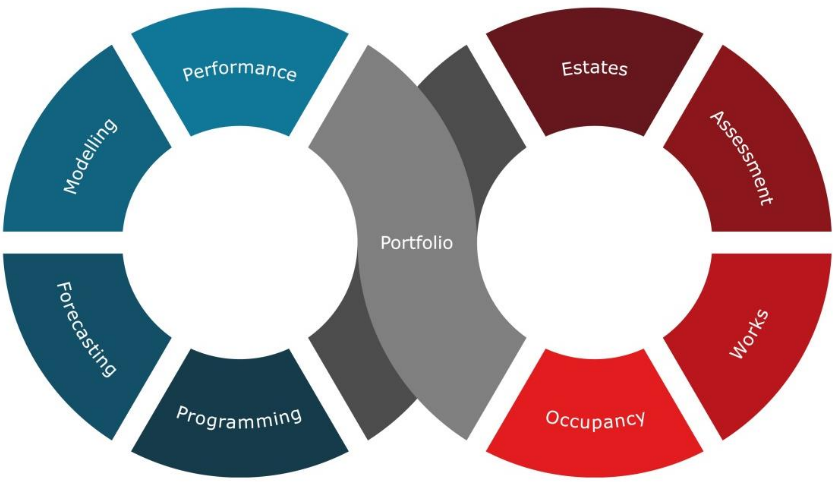


Figure 30: The Atrium Enterprise Asset Management System (Atrium, 2014)

The Manhattan Atrium software is one of the only platforms to offer any sort of BIM integration with LCC. The assets displayed within the Atrium EAM system are linked to the assets captured within the Model through use of the BIM reference fields and Asset ID. This ensures that when 'Auto Highlight to Model' is selected, the user can select an asset within the EAM and this is then highlighted in the model, as illustrated below:

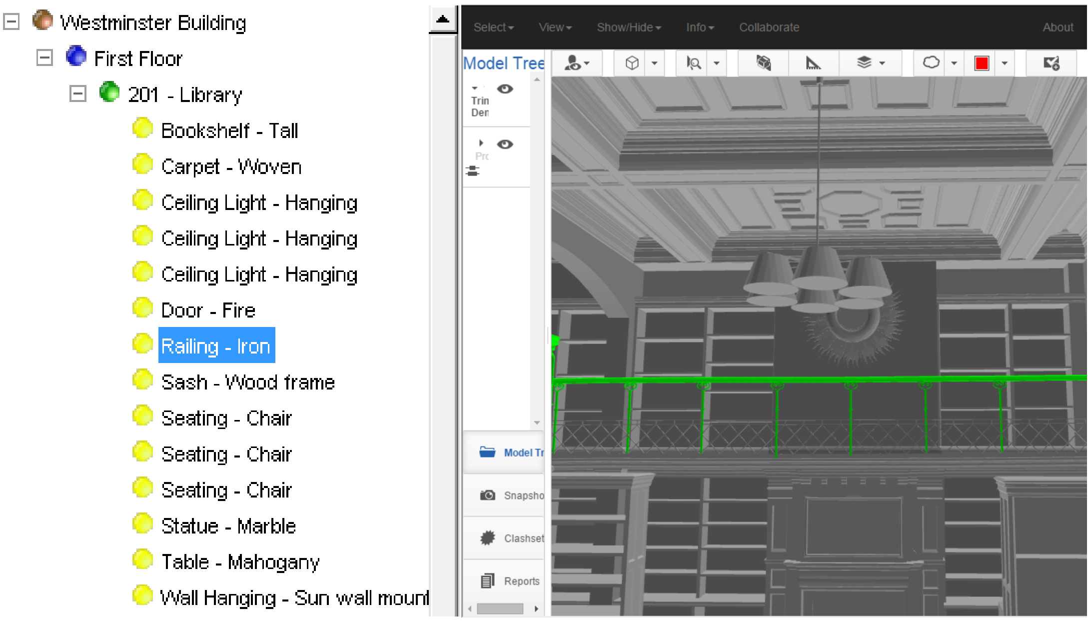


Figure 31: BIM connection with EAM (Atrium, 2014)

This retrospective BIM model has been used to highlight the location of the asset in question. Anything beyond this involves a changing colour which highlights the condition of the asset based on the surveyor's professional opinion. Data collection makes such an approach impossible to apply (on a component level) to HVAC assets such as AHUs because the probe used to scan the environment cannot be placed inside critical assets. The key benefit of using geometry visualisation linked to LCC and AM is that it can tell users about spaces and components they cannot usually see, and the premise of probe-based retrospective BIM is inapplicable in the HVAC aspect of LCC.

4.4 Parametric Generative Design: Rhino Modelling as a Method for Visualising Lifecycle Costing

Performance-based design is defined as the synthesis of two digital design processes, namely, geometry-generations and performance simulation (Oxman, 2006). The generative design process depends on variants which are parametrically defined in relation to the design problem, while the evaluation of generated solutions depends on the simulation of different parameters such as social, cultural, ecological or economic (Kolarevic & Malkawi, 2005). As opposed to common parametric tools such as Revit, Unity 3D and SketchUP, Rhino is a software tool scarcely mentioned in academic literature. A number of recent studies have used Rhino for modelling physical assets (Ercan & Elias-Ozkan, 2015; Wu & Shih, 2014) but not to the elemental level needed nor, as described in the Bew-Richards ramp diagram, at the level necessary for component-level lifecycle modelling.

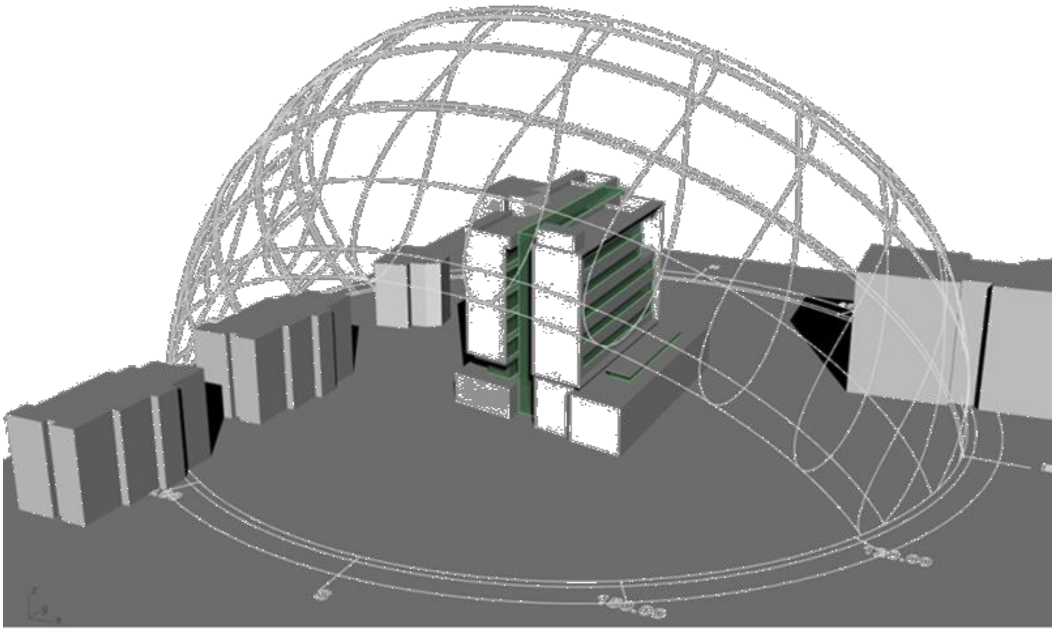


Figure 32: Sun Path and Show simulation in Rhino (Ercan & Elias-Ozkan, 2015)

One of the few studies to use Rhino for modelling such complex assets was the one conducted by Fouchal in 2015. Fouchal's study focused on solving the geometrical complexity encountered in conventional arrangements of building services, while taking into account thermos-physical and electromagnetic interactions between services together with building regulations (Fouchal, Hassan, & Loveday, 2012).

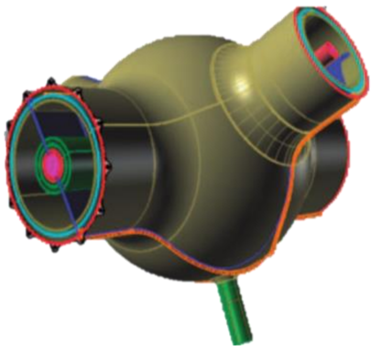


Figure 33: Distribution node for multi service trunking system (adapted from Fouchal, Hassan, & Loveday, 2012)

Fouchal's study was not concerned with asset management or the long-term planning of assets, rather, his research was concerned with ascertaining a novel methodology for grouping building services into a single trunking system with minimal proximal distances between them (Fouchal et al., 2012). However, what this does demonstrate are two key aspects of Rhino's usefulness as a tool. Firstly, its

LoD is high and can display intricate component detail to the level required for an asset management LCC visualisation. Secondly, its layers can be applied to display different colours.

4.4.1 Grasshopper

Grasshopper is primarily used to build generative algorithms, such as for generative art (Loomis, 2011). The main interface for algorithm design in Grasshopper is the node-based editor. Data is passed from component to component via connecting wires which always connect an output grip with an input grip. Data can either be defined locally as a constant, or it can be imported from the Rhino document or a file on the computer. Data is always stored in parameters which can be either free-floating or attached to a component as input and output objects. A recent piece of research on building component environmental simulation conducted by Ercan (2015) cited Grasshopper as the tool of choice. Generation of data or parametric objects is not limited to the built-in components in Grasshopper; it is also possible to exchange data with other add-ons, as inputs and outputs for further computation (Ercan & Elias-Ozkan, 2015). Ercan's study was based on finding the optimal shading geometry for louvers using Grasshopper as the computational engine to perform the simulations.

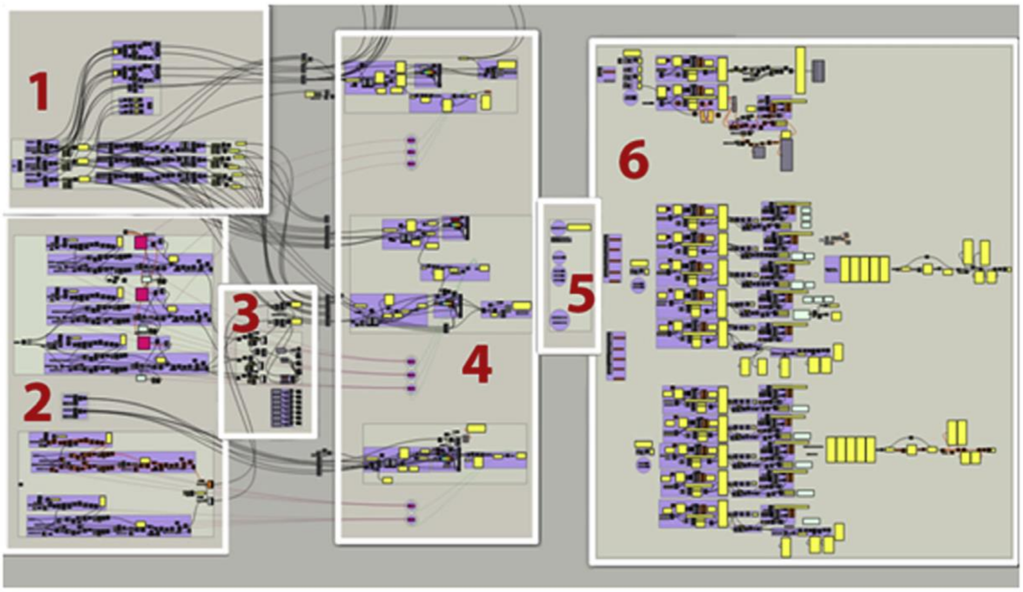


Figure 34: Grasshopper organisation for performance-based parametric design explorations (Ercan & Elias-Ozkan, 2015)

The Grasshopper design in this research comprised six components connected to each other in accordance with the design approach which defined the workflow. These were as follows (Ercan & Elias-Ozkan, 2015):

- Mesh geometric definitions
- Shading device geometric definitions
- Building geometry import components

- Simulation components
- Control centre for analysis
- Data recording and reading group

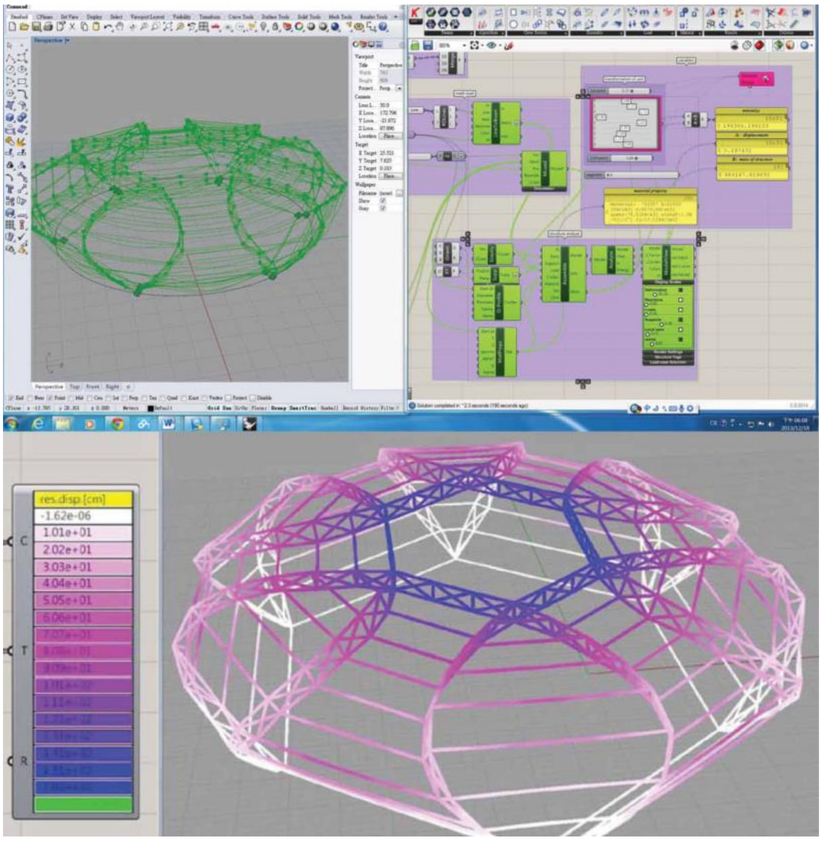


Figure 35: The quantitative and intuitive presentation of structural form and cost by dashboard (Wu & Shih, 2014)

Another study looked at utilising Grasshopper as a means of presenting real-time analysis, using Monte Carlo simulations as a means of exploring early design stages (Wu & Shih, 2014). The tool was designed with the architect in mind and used a combination of Rhino, Grasshopper and excel data to visualise the parametric relationship between the orientation of a building mass and heat gains. The study demonstrated Grasshopper's ability to investigate cost trade-offs for structural elements and visualised this cost in an innovative and intuitive way. Above illustrates how the tool can be used to visually differentiate between the costs of components. The tool can provide a dashboard for the end user to aid in their understanding of what assets are the most expensive and where they are.

Chapter Summary and Findings

- Assets are risks, and the visualisation of risks and strategy to deal with them that current techniques 3D techniques basd on the IFC schema do concisely capture.
- 3D geometry produced as a result of the BIM process can form the foundation on which lifecycle data visualisations can be built.
- Intersecting vertices should be avoided and removed where possible to reduce runtime and to contribute to the texture-translation issues.
- Data-heavy models: There is no easy and automatic way to simplify the geometries and reduce the polygon counts. The model needs to be created with minimum complexity.
- Object nomenclature: It is a good idea to name objects in a model in a unique manner (not just a series of numbers of ‘wall 42’ for example.
- There is a lack of interoperability when using the ‘collaborative’ IFC format, which is written and interpreted differently by each software vendor.
- The concept of being able to display dynamic-asset condition through visualisation can only be realised through colour, which Rhino can display.
- The Rhino and Grasshopper plugins are considered to offer the best possibility for achieving operational lifecycle modelling.

Chapter 5. Research Methodology and Design

5.1 Decisions Informed from Literature prior to undertaking Research Methodology

This research – as defined in Chapter 1 – aims to develop a data-driven risk-based lifecycle replacement funding model and visualisation tool to improve the decision-making of mechanical assets in the PFI Healthcare sector.

The literature review covered the key aspects around life cycle costing, asset management and data visualisation. Based on the review of literature carried out, the following decisions have been informed prior to undertaking the research:

- The case study hospital should be post-construction phase (i.e. in its operational lifecycle phase) and should have a pre-existing BIM model available.
- The capital cost element is not included within the scope of this study.
- Acquisition costs shall not be included in the research scope.
- The model should assume no income from 'selling' the asset (i.e. disposal costs)
- End of Life Costs shall not be included in the analysis.
- The term discount/ inflation rates should mimic the current lifecycle model figure of 2.5% currently in use for HCPs lifecycle model.
- The ISO 15686 Factor Method will be used as the descriptor reference for this research.
- The model shall not consider design and installation risk in the scope of the study.
- The thesis will minimise the number of damage mechanisms and only include key aspects (such as those mentioned in ISO 15686 Part 8) to ensure model complexity is optimised.
- The model will assume that the SPV's management of the operations and facility falls under the umbrella of compliance. This will allow the LCC model to take a more financially geared view.
- The lifecycle model will consider the ISO guidance concerning service life data selection.
- The tool should be based on real data.
- This model should set about drawing upon operations and maintenance (O&M) data physically collected from other hospital projects across the United Kingdom. The serviceable life of an asset's component is of critical importance and should feature as a key facet of the research design. .
- Data collection across multiple hospital should go some way to removing the notion of silos and culminating data into one repository.
- The Rhino and Grasshopper plugins offer the possibility for achieving operational lifecycle modelling. Autodesk and other tools rely too extensively on the IFC schema. Modelica models are too data intensive and have already cited drawbacks such as computational time needed to simulate, economic barriers to its uptake and user training necessities.

5.2 The Physical Asset Lifecycle Model Framework

This chapter explains the development of the risk-based LCC model of a case study hospital building. It will look to compare the hypothetical financial profile resulting from the risk-based model with the current financial profile for the AHUs.

The data collection data sources are as follows:

- Existing: CIBSE best practice guidance (secondary data collection)
- New: Asset failure and cost data recorded across HCP Social Infrastructure sites (primary data collection)

Option two above included physically visiting various sites across the UK. A mobilisation schedule and data collection timeline across the sites was prepared.The data visualisation tool selected for the study was Rhino 5. Rhino 5 is a tool which has been severely under-used in this context yet demonstrates all the credentials required to perform the required simulation. It was also chosen for its ability to import Navisworks 3D files, thus avoiding the IFC schema and its subsequent complexity. Another benefit was due to its Grasshopper plugin, which allowed for dynamic three-dimensional heat-mapping and data communication between Microsoft Excel CSV files (the standard format for lifecycle modelling and a reliable program which is unlikely to be replaced in the near future).Below outlines the research components involved in the research. The physical asset lifecycle model (PALM) architecture diagram is a quantitative-based approach.

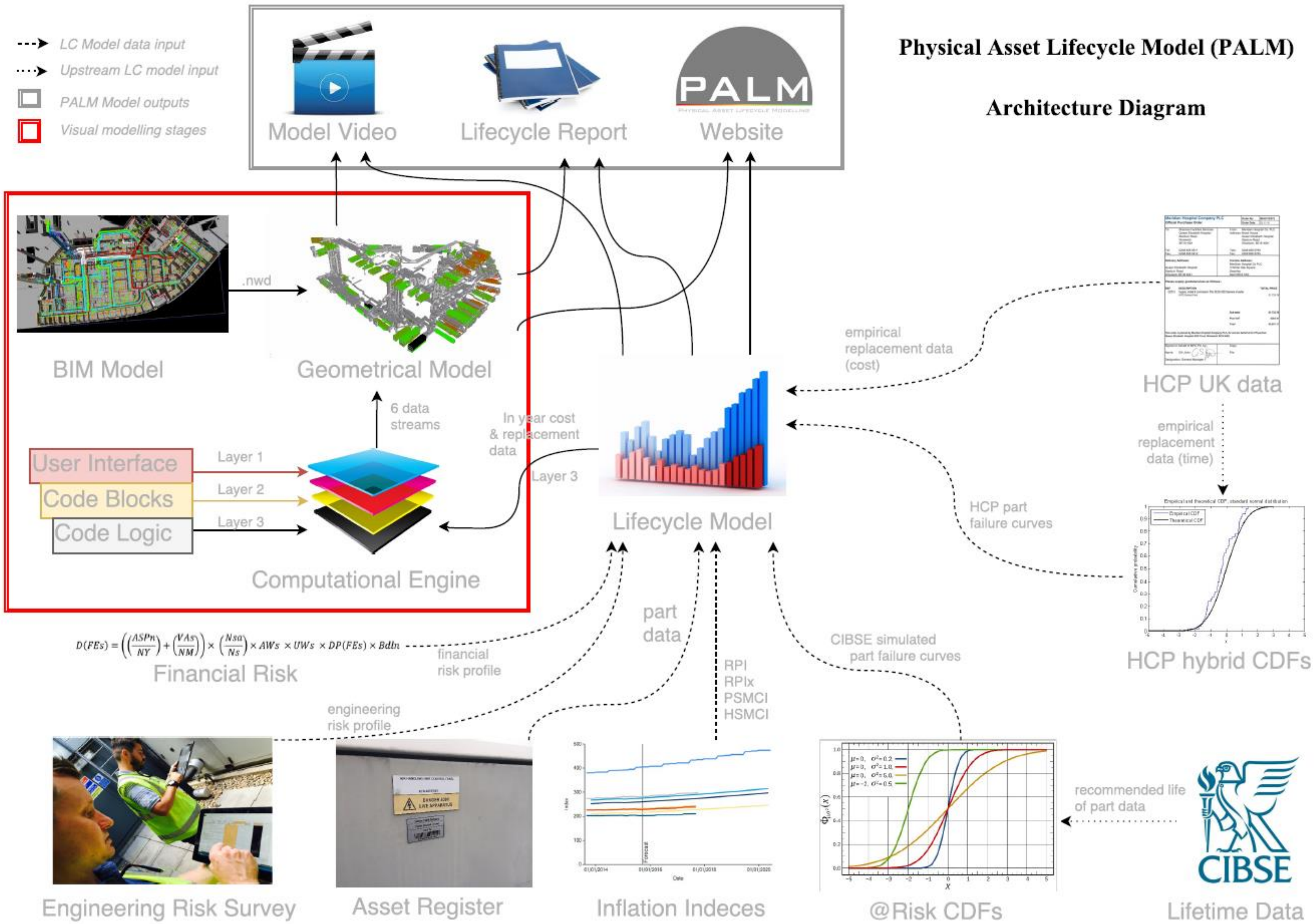


Figure 36: PALM Architecture diagram

5.3 The Proposed Research Approach: the Quantitative Framework

A numeric or statistical approach to research design is what constitutes a quantitative research method (Williams, 2007). The quantitative research approach is specific in its surveying and experimentation methods as it builds on existing theories (Leedy and Ormrod, 2001). The research itself is independent from the researcher and, as a result, data is used to objectively measure reality. Quantitative research creates meaning through objectivity uncovered in the collected data (Williams, 2007). In this setting, the quantitative data used is composed of a combination of empirically collected samples (HCP managed hospital facilities) or recognised institutional data sources (CIBSE Guide M).

Quantitative research involves harvesting data so that the information can be quantified and subjected to statistical treatment in order to support or refute alternative knowledge claims (Cresswell, 2003). There are three broad classifications of quantitative research: descriptive, experimental, and causal comparative (Leedy and Ormrod, 2001). The descriptive research approach examines the situation as it exists in its current state, and involves the identification of attributes of a particular phenomenon based on an observational approach (Williams, 2007).Experimental research can be further subcategorised into three types of exploratory approaches: experimental, true experimental, and quasi experimental.The following table has been developed following a epistemologically quantitative focused review of literature in the field:

Table 11: Summary of quantitative, qualitative and mixed method approaches

Research Approach	Knowledge-Theory position	Method	Research Use
Quantitative	Pre-experimental design True experimental design Quasi experimental design	Predetermined statistical analysis	Tests or verifies Observes and measures Unbiased Validity standards Identifiable variables
Qualitative	Narrative design	Text and image analysis Open ended Interviews and questionnaires	Collects participant feelings Appreciates personal values
Mixed-methods	Mixed design	A mixture of the above	A mixture of the above

The following aspects of the model were considered:

- Research Environment: The research was conducted in the field of the built environment. The built environment and FM industries are highly quantitative – particularly within PFI – due to the financial underpinning of the industry. The research involved very little human interaction apart from dealing with the on-site FM teams and the engineering risk-survey process.

- Research Focus: The research is a realist piece in nature but is based on producing and comparing outputs which are currently derived through what is essentially a quantitativeapproach in the industry. With modelling and post-modelling stages being solely quantitative.
- Research Objectives: The research objectives are quantitative because the key output of the model is a financial profile for the replacement of assets.
- Research Novelty: The type of research is an amalgamation of currently independent topics including BIM, cost modelling, risk modelling and life cycle costing.

5.3.1 Operationalisation of the Research: Methods and Purpose

Data should be collected using different strategies, approaches and methods in such a way that the resulting mixture or combination builds on the strengths and minimises the weaknesses of the single approach (Brewer and Hunter 1989, Fretchling and Sharp 1997, Raslan, 2010).

An initial data collection on the assets within HCP1) was conducted (the asset register, AHU drawings, operation and maintenance manuals, BIM model followed by data collection from other hospitals (HCP 2 – HCP18 – primary quantitative) across the UK and current best-practice guide lifetimes (secondary quantitative). Further data was collected through an engineering-risk survey (quantitative) and financial-risk data (otherwise known as pay-mech risk) was also collected (quantitative).

A clear distinction should be drawn between HCP1 and HCP2- 18 at this stage:

HCP1: The case study hospital. This is the hospital which is used for data analysis only.

HCP2 – 18: The remaining hospitals in the study, used for data mining purposes only.

5.3.2 Asset Register and other Data Collection of HCP1

5.3.2.1 Description

Data collected in the following ways formed the basis for the model:

- AHU Asset Register – This contained invaluable information such as:
    - Asset code (for use when surveying), phase, floor number, room number, hospital area (for use when establishing financial risk), manufacturer, serial number, supplier and general notes.
- Operation and Maintenance Manuals
- AHU drawings

    - The number of components within each AHU, the location of the components, AHU dimensions, fan speeds, motor kW outages (see example in Appendix 2).
- Hospital Plans
- BIM model
    - Only geometrical data as well as an AHU componentry list for cross checking against the asset register was read.

5.3.2.2 Purpose

The purpose of collecting this data was two-fold:

- To ensure that the lifecycle model directed that individual AHU components (of which there are 1247) be replaced according to the correct and most up-to-date data.
- To provide a geometrical skeleton on which to visually model the replacement cycle.

5.3.3 Data Collection of HCP2 - 18

5.3.3.1 Description

The data sampling from UK hospitals involved contacting the on-site teams at various locations around the UK and collecting information on component replacement and cost information. The full 32-point data collection sheet can be found in Appendix 3.

5.3.3.2 Purpose

The purpose of this exercise was to determine what types of componentry within AHUs across the portfolio were likely to fail and what the cost of replacement was likely to be. By collecting this data, the lifecycle model produced would be based on a more robust data set pertaining specifically to AHUs within hospitals within the United Kingdom.

5.3.4 CIBSE Lifetime Data

5.3.4.1 Description

Due to the age of the various hospital estates within the portfolio and due to the fact that none had reached their recommended replacement life, from an asset perspective (20-25 years), CIBSE Guide M data for components was collected. A regression model grounded by a theory presented prior (3.4.2) which states that for each and every level of *X*, there exists a probability of *Y* (Kirkham, 2002) is the basis for distributing generic mean data from CIBSE.

5.3.4.2 Purpose

The purpose of collecting recommended component data from secondary sources is two-fold:

- The data will inform the @Risk Monte Carlo simulated statistical distributions which will provide toll flexibility and allow the decision-maker to choose their risk-appetite level (the 'conservative', 'balanced' & 'optimistic' approach).
- The data will inform the profile beyond the empirical data collected from the HCP UK data and allow for a hybrid profile (i.e. a combination of real and simulated data) to be produced (the 'recommended' approach).

5.3.5 Engineering-Risk Survey

5.3.5.1 Description

The engineering-risk survey was conducted using two professional surveyors with affiliations to recognised bodies (RICS and CIBSE) and a detailed knowledge of HVAC systems. The survey is based on the ISO 15686 standard.

5.3.5.2 Purpose

The purpose of the survey was to provide an engineering 'risk profile' on each AHU which would subsequently impact the replacement profile through combining the results of the survey with the results of the financial risk formula, thus enabling the differentiation between each asset, based on key industry recognised life-cycling impact factors.

5.3.6 Financial Risk

5.3.6.1 Description

The financial-risk formula was based on the payment mechanism outlined in the management services agreement between the MSP and NHS. The formula considers aspects of service delivery impact categories and the financial impact of failure per AHU.

5.3.6.2 Purpose

The purpose of the inclusion of the risk formula was to pair the results of the risk level (based on the financial impact of a potential failure – i.e., the impact of the failure of one AHU may be financially less or more critical than the failure of another) and combine the results to form the engineering risk survey. Both risk outputs would be equally weighted to provide a risk profile for each AHU based on two different types of risk.

5.3.7 Research Quality: Validity Considerations

The validity of research studies can be differentiated into design validity, which pertains to the credibility and trustworthiness of derived conclusions and inferences, and information validity, which relies on the quality and reliability of the information/data on which conclusions are based (Raslan, 2010). Therefore, the following points should be carefully observed when collecting and analysing the data:

- Data Source: Is the data coming from a reliable source? This is dependent on the consistency of the data collected and will impact the inferences drawn.
- Interpretive distinctiveness: How can the inferences of the data differ from other explanations of the results?

Individuals usually accept sensory knowledge as truth because it provides a level of evidence which one can withstand or challenge (Williams, 2007). However, in the context of producing lifecycle predictive models, computation visualisations and financial-planning proposals, it is important that the output obtained be metrically verifiable when subjected to the quality-assurance process. As a measure of the model's validity, the Head of Financial modelling and the Head of Technology management at UCLs Mullard Space Science Laboratory were tasked with reviewing the formulaic disposition (design validity) and statistical distributions (information validity) on which the asset replacement predictions of the model were based.

5.3.8 Data Protection and Ethical Practice

The following has been agreed after discussions with HCP:

- To anonymise the names of the surveying team conducting the engineering-risk survey
- To anonymise the names of the hospitals in the survey
- To anonymise the specific financial figures relating to the portfolio
- To use only the figures which are freely available from Companies House
- To anonymise the names of any HCP staff in the appendices

There are no foreseen procedures to take regarding ethical practice for issues such as informed consent or respondent validation.

5.4 The PALM Methodology

The LCC modelling methodology comprised the following steps:

1. Collection of HCP1 AHU data including operation and maintenance manuals, runtimes, as-built drawings, installation dates and replacement data for the 113 AHUs. The HCP1 asset register and BIM model were also collected.
2. A review of the AHU as-built drawings.. There were found to be over 1,100 components within the 113 AHUs.

3. A physical-condition survey of the AHUs taking into consideration the seven aspects impacting service-life prediction (as given by ISO 15686 – see Chapter 3) to create a risk level for each AHU and its subcomponents.
4. Collection of replacement data across HCP 2-18including 36 data points for each failure, the runtime for the equipment, the cost of the part and its installation date.
5. Creation of the subcomponent failure curves based on the data collected from HCP 2-18.
6. Creation of the subcomponent failure curves based on CIBSE data.
7. Creation of the life cycle cost model..

The geometrical modelling methodology comprised the following steps:

- Collection of HCP1 BIM model and conversion from .NWD to .FBX to .3dm file.
- Assimilation of the models and a data-cleansing exercise to reduce the model weight and improve performance.
- Merging of the meshes on a component level.
- Assignment of meshes according to the components stated in the as-built drawings collected from HCP1.
- Setting up of the New Rules of Measurement (NRM3) structure for user navigation.
- Creation of the Grasshopper visual engine to be plugged into the geometrical model. This also included the creation of the PALM plugin for future users to be able to create their own models more rapidly through the packaging of code.

In terms of the approach adopted, this can be seen as an emergent methodology. Currently, geometrical modelling and lifecycle cost modelling have had almost zero interaction because of the nature of where each occurs during the building's lifecycle (BIM – construction, Lifecycle – operation). The notion of visualising plant condition for the purpose of long-term planning (as opposed to short term, energy consumption, carbon emissions, etcetera) (Ercan & Elias-Ozkan, 2015; Fouchal et al., 2012) is a novel concept.

5.5 HCP1 – The Case Study Hospital Building

HCP1 is a large acute care NHS facility in the City of London. Built between 2010 and 2014, the facility was constructed over two phases and includes state-of-the-art medical amenities (including seven operating theatres served by the AHUs) as well as mechanical plant rooms and FM facilities. HCP1 is a steel-framed building with concrete cladding. The gross floor area is approximately 52,716 m^2 (phase one 23,547 m^2; phase two 29,169 m^2) and spanning eight stories, the gross volume is approximately 158,148 m^2.

HCP1 contains 113 AHUs, valued at circa £6,100,000. Through a comprehensive review of the as-built drawings, the following AHU subcomponents have been found at HCP1 (Table 12 below).

Below shows the AHU components currently on site. There are 1,247 components within all the 113 AHUs at HCP1, giving an average of 11.04 components per AHU. The AHU-to-component ratio gives the numbers of each component you may expect to find in an AHU, based on those observed at HCP1.

Table 12: Component breakdown and manufacture

Component	AHU1 Qty.	Ratio (AHU: Component)	Manufacturer	Based at
Cooling coil	57	1 : 0.52	DBM/ Luvata	Cramlington/ Welwyn, UK
Frost coil	32	1 : 0.29	DBM/ Luvata	Cramlington/ Welwyn, UK
Heating coil	72	1 : 0.65	DBM/ Luvata	Cramlington/ Welwyn, UK
Run around coil	103	1 : 0.94	DBM/ Luvata	Cramlington/ Welwyn, UK
Control panel	94	1 : 0.85	Unknown	Unknown
Supply fan	65	1 : 0.59	Comefri	Unknown
Extract fan	63	1 : 0.57	Comefri	Unknown
Flatbank filter	107	1 : 0.97	AAF	Northumberland, UK
Polyseal filter	38	1 : 0.35	AAF	Northumberland, UK
Other filter	14	1 : 0.13	AAF	Northumberland, UK
Humidifier	27	1 : 0.25	Spirax Sarco	Cheltenham, UK
Inverter	147	1 : 1.34	Unknown	Unknown
Motor	181	1 : 1.65	AmTecs Ltd	Berkshire, UK
Shut-off damper	105	1 : 0.95	Aerotermica	Milan, Italy
Silencer	142	1 : 1.29	Allaway Acoustics	Hertford, UK
AHU Total	1247 components	11.04 components/ unit	McQuay (Daikin)	Dartford, UK

This information has implications for the data collection across HCP2-18 because these ratios will be used to extrapolate how many parts there are on any given healthcare project, based on the number of AHUs. All of the components are available through sales offices or warehouses in the UK, save the damper manufacturer *Aerotermica*. The coil manufacturers are DBM and Luvata respectively. The coils are the only components with an alternate manufacturer, raising benchmarking possibilities and economies-of-scale purchasing, as opposed to the latter where there is only a sole manufacturer.

The AHU runtimes were ascertained through consultation with the SFS building management system (BMS) team. The AHUs have weekday/weekend scheduling. The majority of the units operate for 24 hours per day, 7 days per week. However, there were a number which had slightly reduced runtimes on weekdays or at weekends, such as the supply and extract units serving the cardiac theatre suites.

In accordance with ISO 15686, the following table details which of the following methodologies have been used for predicting or evaluating unit lifespans during this study:

Table 13: Methodology used to predict life (adapted from ISO 15686:2008)

Data Collection Method	Used?
Fundamental studies	
Field exposure	✔
Inspection of the building and constructed assets	✔
In-use exposure	✔
Accelerated short-term exposure	
Short-term in use exposure	
Judgement based on expert experience	✔
Judgement based on experience in the market	
Other	
Unknown	

5.6 HCP UK Data

5.6.1 Data Elicitation from the HCP UK Hospital Portfolio

Working for the management service provider involved working and researching in HCP's head office meant that operational data was not easily accessible without contacting and physically visiting the site. HCP's client portfolio consists of a combination of healthcare, education and accommodation facilities. The scope of the data-collection exercise involved only healthcare facilities and this is illustrated below.

The distribution of the portfolio stretches across the UK. The healthcare projects are run in England, with one project included from Scotland. In total, 16 hospitals within HCP's portfolio have been included (in red) as well as one other hospital, located in Oxford (in orange), outside of HCPs management. The remaining education and accommodation facilities (in grey) will not be included in the study.

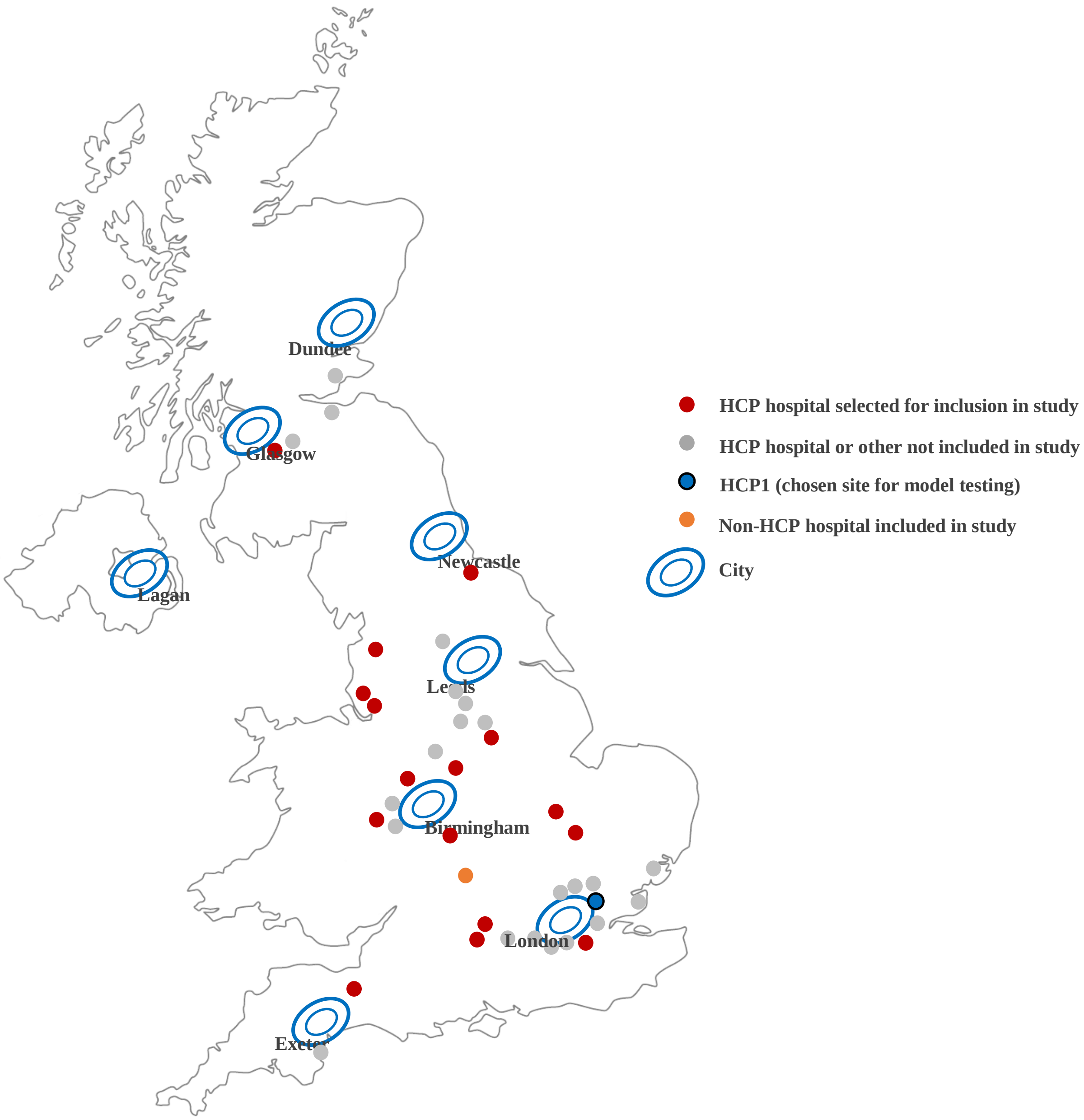


Figure 37: UK map showing facilities considered in the data collection and scope of the study

In order to gain access to the projects and collect the information a number of contractual and political loopholes had to be surmounted. As shown in Figure 2 the MSP has responsibility for managing the SPV, yet it is the SPV's subcontractors which hold a vast amount of the data required for the analysis since it is *they* who are maintaining, repairing and replacing the equipment. The MSP has *no* contractual agreement between the project-level HFM subcontractors and so an appropriate plan had to be drawn up as to how to collect this data. The allowance was given by the board for contact to be made top down, as shown in Figure 38 below:

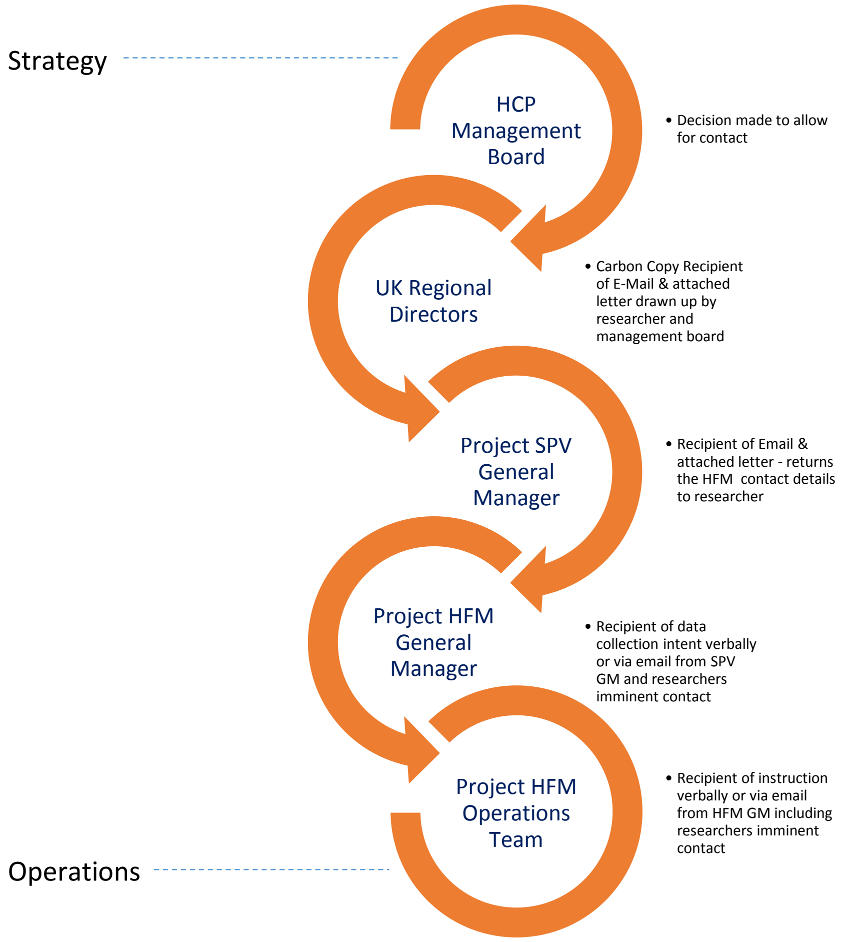


Figure 38: Diagram to show top down route to making contact with the project HFM operations team

Contact was made by letter (see Appendix 4). The letter outlined the scope of what was to be collected and was addressed to the SPV General Manager (GM). The SPV GM was then asked to make contact with the HFM-subcontractor GM, to pass on to the appropriate engineer. At that point a date was arranged for visiting the site to collect the data. Where necessary, contact was also made by Babajide Ogunniyi (the Head of Asset Management for HCP's SAM team) via email, to raise the profile of the research for those working at the operational sites (see Appendix 5). From this point, a data-collection management sheet was created to monitor the progress of the data collection, what had been sent and who had been contacted at each site.

5.6.2 Hospitals within HCP 2-18 included in the Study

The table below illustrates the method for inclusion of hospital data in the study. There were three primary reasons for a hospital to be excluded from the study, these being:

- **Data not being recorded** – this could be as a consequence of poor subcontractor management or a change of HFM team on site due to poor performance meaning the data was not stored/transferred.

- **HFM holds the lifecycle risk** – where the HFM team was executable for lifecycle, the SPV management team had no right to demand part replacement or cost information.
- **Facility age** – in some instances the hospitals were newly built and therefore provided almost zero replacements due to their infancy.

Table 14: Hospitals for inclusion in the study based on qualification matrix

HCP No.	Data not being recorded/ available	HFM holds the Lifecycle Risk	Facility age	Included in study?
2				Y
3	x			N
4				Y
5	x			N
6				Y
7	x			N
8				Y
9			x	N
10	x			N
11		x		N
12		x		N
13			x	N
14		x		N
15	x			N
16				Y
17				Y
18			x	N

Six hospitals were considered as being suitable for data mining, the remainder were excluded for reasons set out above. Supporting evidence and examples of instances where hospitals could not be included in the study can be found in Appendix 6. For the generation of new data, the methodology as described in ISO 15686-2 (2012) should be used (BSI, 2008). One of the greatest benefits of the method of data collection and its subsequent output once modelled is its level of realism.

Meridian Hospital Company PLC
Official Purchase Order

Order No:	**MHC/10/272**
Order Date:	23.11.10

To: Skanska Facilities Services Queen Elizabeth Hospital Stadium Road Woolwich SE18 4QH Tel: 0208 836 5611 Fax: 0208 836 5612	From: Meridian Hospital Co. PLC Address: Brook House Queen Elizabeth Hospital Stadium Road Woolwich, SE18 4QH Tele: 0208 836 5799 Fax: 0208 836 5795
Delivery Address: Queen Elizabeth Hospital Stadium Road Woolwich SE18 4QH	**Invoice Address:** Meridian Hospital Co PLC 3 White Oak Square Swanley Kent BR 8 7AG

Please supply goods/services as follows:-

REF	DESCRIPTION		TOTAL PRICE
Q2312	Supply, install & commission 1No SED2-32B Siemens Inverter (HT2 Extract Fan)		£1,733.76
		Sub-total	**£1,733.76**
		Plus VAT	**£303.41**
		Total	**£2,037.17**

This order is placed by Merdian Hospital Company PLC, for and on behalf of its PFI partner Queen Elizabeth Hospital NHS Trust, Woolwich SE18 4QH.

Signed on behalf of MHC Plc. by:- Name: Gill Jinks Designation: General Manager	Copy: File

Figure 39: example invoice from HCP 2

5.7 Lifetime Data

The following chart displays the recommended life of AHUs on an asset (green) and component or part (blue) level – as according to CIBSE Guide M.

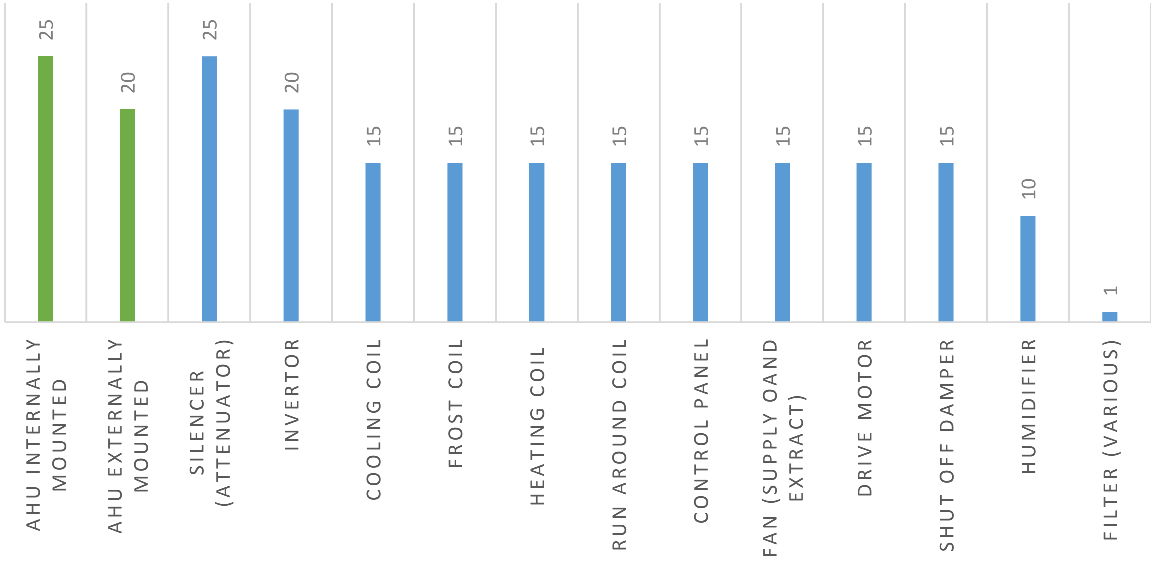


Figure 40: Asset and part lifetimes (CIBSE: Guide M, 2012)

The green indicates the asset lifetimes and the blue indicates the component-part lifetimes. What is clear is that CIBSE differentiates between internally and externally mounted AHUs and puts the recommended life discrepancy down to the external environment conditions (for example, rooftop AHUs are subject to the elements which internally mounted AHUs are not).The blue bars indicate the standard lifetimes for the components under analysis.

5.8 The Engineering-Risk Survey

A quantitative-risk assessment is something which has been discussed in previous chapters. In this research a quantitative-risk assessment was formulated for the purposes of collecting data on the AHUs. It was viewed as a good tool to incorporate in the project because it took into account some of the site-specific factors, giving the lifecycle strategy corporate level reliability and operational level support by incorporating the views of operations team members on the performance of the AHUs and their components. The quantitative-risk assessment is captured in spreadsheet format and can be seen in Figure 41.

5.8.1 Integrating the Factor Method and IPFM Proforma

Allowing adequate space for maintenance and equipment replacement is very important. Where the particular reference standard is in doubt or where equipment has been 'shoe-horned' into a confined space, a variation factor should be applied (CIBSE, 2008). It was aspects such as this which the proforma attempted to identify. The sever factor categories are as follows:

- Factor A. Inherent performance level
- Factor B. Design level
- Factor C. Work-execution level
- Factor D. Indoor environment
- Factor E. Outdoor environment
- Factor F. Usage conditions
- Factor G. Maintenance levels

The survey was conducted over a period of two months during which all 113 AHUs were assessed and assigned a risk level. The two surveyors were industry-recognised competent engineers - a mechanical and electrical-asset surveyor from the HCP Strategic Asset Management team, and the Operations manager for Skanska. The former (Mr HCP) was selected for his extensive experience in M&E surveying and his understanding of carrying out the survey. The latter (Mr Skanska) was selected for his extensive experience in physically maintaining the AHUs under analysis. As a member of the HCP1 on-site subcontracting team, he was also thought suitably qualified carry out the survey. In addition to this, having two surveyors from different companies provided two key benefits. Firstly, the results from the two separate surveys could be averaged out to provide a more accurate risk level (if one surveyor was more risk averse than the other). Secondly, because Skanska is a subcontractor for HCP1, it meant that the results produced provided a tempered and well-balanced view from both a strategic view point (Mr HCP – being responsible for providing lifecycle plans for HCP1) and an operational view point (Mr Skanska – being responsible for implementing lifecycle plans for HCP1).

The table below provides an explanation as to how the risk exposure should be understood by the surveying team. In terms of categorical importance rankings and their subsequent impact on the risk level for each asset, the surveyors were asked to assign 'years' of degradation to any category they chose. For example, if the AHU under survey was roof-mounted, the surveyor could assign the 'worst case' scenario as zero for Factor D – Indoor Environment, because there is no indoor environment present in this case. The number of years surveyors could assign across the various factor categories was 17. This is because, as discussed during the literature review, the current best guide for AHU replacements is between 10 and 27 years. What the BCIS is saying here is that the very best AHU can be expected to last for 27 years, while the very worst can be expected to last just 10. While the data set underpinning the BCIS results is small, it will suffice for the purpose of the exercise. So, the surveyors had to assign a 17 year 'range of influence' across the categories, too few or too many years resulted in a syntax error alerting the surveyor that their figures were skewed. However, during the calculation stage it became apparent that the order-ranking method was partially invalid. This was due to surveyor preference towards an equal importance method for their survey. They suggested that by having an equal importance method as a baseline, they could focus more on assessing and assigning the correct risk-exposure probability. Equal weights were thereby calculated as the control. On assigning the year range of influence, the surveyors next had to assign an in-use condition grade to each category.

There were certain rules to which the surveyors had to adhere (e.g., Factor categories D and E could never both have years assigned against them on the same survey, and the inherent performance level should never be described as 'n/a'). These rules were built into the pro forma tool so that if the surveyor accidently broke a rule, the survey would respond and alert them.

University College London & HCP Social Infrastructure UK
Risk Appraisal - Life-cycle replacement prediction pro-forn
Qualitative Failure Data Collection
Asset - Air Handling Unit

UCL | hcp intelligent management of assets

Unit Description	
Unit Number	AHU 01E
Maintainer	
Inspector	Mr A. Darge - Mechanical & Electrical Surveyor - HCP
Date	22.07.2015

Project	St Bartholomews Hospital Air Handling Unit Lifecycle Survey	Asset	6.6 Space Heating and Ventilation
Scenario	1 (One)	Component	Air Handling Unit 01E

Life Expectancy Projection	
BCIS Max Life	27
BCIS Min Life	10
Maximum loss	17

	Aspect of interest	Risk Exposure Factor/ Category	Risk exposure Factor Description	Contribution to loss of life-hours: Impact of Worst Case	Grading	Percentage	Probable Loss
Technical	Inherent quality characteristics	**Factor A.** **Inherent Performance Level**	The grade of the component as supplied in the long term.	0	Not Availabile	0%	0
		Factor B. **Design Level**	The components installation in the building and is typically based on the level of shelter and protection from agents provided by the design of the building.	0	Not Availabile	0%	0
		Factor C. **Work Execution Level**	The level of skill and control in site work. It is based on whether the site work is in accordance with manufacturers' recommendations and tightly controlled including assets such as storage, protection during installation, ease of installation etc.	0	Not Availabile	0%	0
	Environment (The general use of the building is taken into account, together with relevant local aspects. Indoor and outdoor environments are separated and for most components only one such factor category applies.)	**Factor D.** **Indoor Environment**	The exposure of the object to indoor agents of degradation and their severity.	0	Not Availabile	0%	0
		Factor E. **Outdoor Environment**	The exposure to outdoor agents of degradation and their severity. A meso- or local-level designation can be adequate (e.g. coastal, polluted) for this factor category.	0	Not Availabile	0%	0
	Operating Conditions	**Factor F.** **Usage Conditions**	The effect of use of the building/ constructed asset. The specific use of the space where the asset is installed/ constructed is likely to be relevant (i.e. communal spaces being subject to greater wear and tear).	0	Not Availabile	0%	0
		Factor G. **Maintenance Level**	The level of maintenance assumed. For certain components that are accessible or require special equipment for access, a particularly low maintenance level should be considered.	0	Not Availabile	0%	0
			Current total - hours	0			
			Maximum loss - hours	Error			

Life Expectancy Projection value: 27

Probable loss (hours)	0
Total Predicted Loss - hours	0
Total Predicted life-cycle - hours	27
Technical Risk Level	Max Loss Error

The worst case total must always be the same as the maximum loss predictio. If this is the case cell F45 will read 'TRUE'

Figure 41: Engineering risk appraisal -lifecycle replacement proforma

Table 15: Risk exposure factor category and description for surveyors' use

Aspect of interest	Risk Exposure Factor/ Category	Risk exposure Factor Description
Inherent quality characteristics	**Factor A.** **Inherent Performance Level**	The grade of the component as supplied in the long term.
	Factor B. **Design Level**	The components installation in the building and is typically based on the level of shelter and protection from agents provided by the design of the building.
	Factor C. **Work Execution Level**	The level of skill and control in site work. It is based on whether the site work is in accordance with manufacturers' recommendations and tightly controlled including assets such as storage, protection during installation, ease of installation etc.
Environment (The general use of the building is taken into account, together with relevant local aspects. Indoor and outdoor environments are separated and for most components only one such factor category applies.)	**Factor D.** **Indoor Environment**	The exposure of the object to indoor agents of degradation and their severity.
	Factor E. **Outdoor Environment**	The exposure to outdoor agents of degradation and their severity. A meso- or local-level designation can be adequate (e.g. coastal, polluted) for this factor category.
Operating Conditions	**Factor F.** **Usage Conditions**	The effect of use of the building/ constructed asset. The specific use of the space where the asset is installed/ constructed is likely to be relevant (i.e. communal spaces being subject to greater wear and tear).
	Factor G. **Maintenance Level**	The level of maintenance assumed. For certain components that are accessible or require special equipment for access, a particularly low maintenance level should be considered.

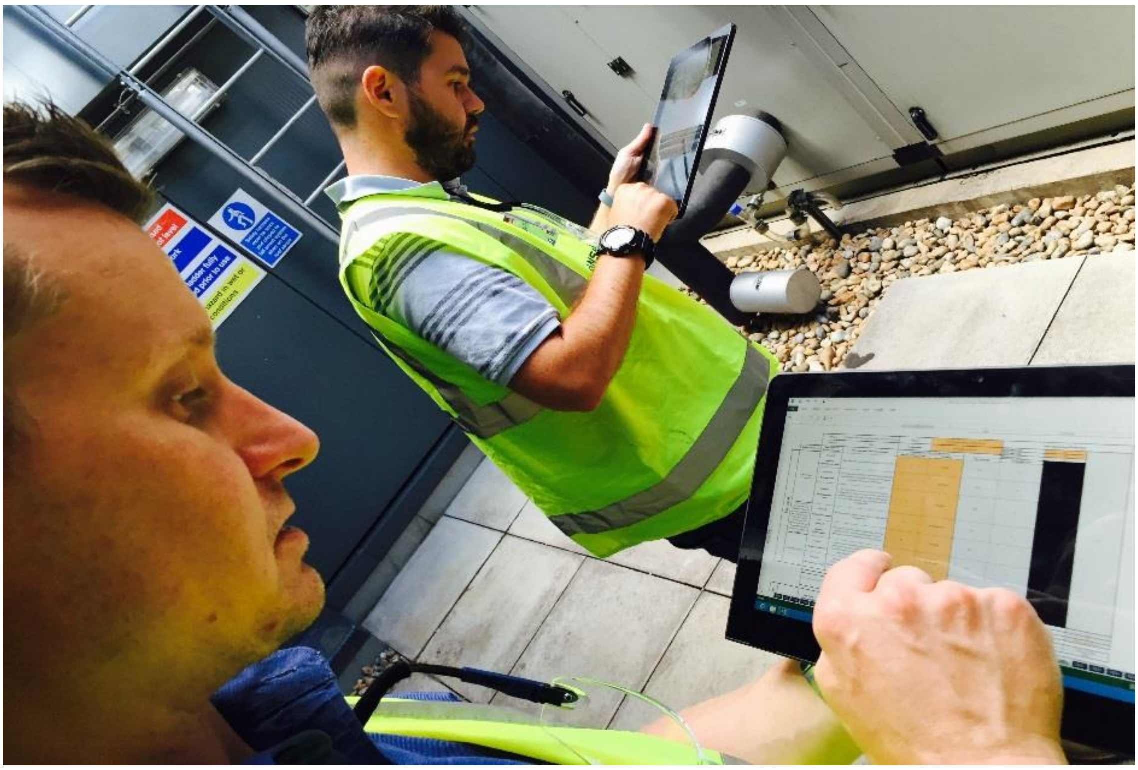


Figure 42: The surveying team using the engineering risk pro forma when surveying HCP1

It was decided, after analysing the results with the surveyors, that the rank-sum method of weighting the components best represented the likely risk level. The reason for this selection was that there would have been no direct link between the risk-exposure probability assigned and a retrospective equal-weight method.

5.9 The Payment Mechanism

The payment mechanism (known colloquially in the industry as 'paymech') is the amount of money to be deducted from the service payment (previously referred to as the unitary charge – UC). The paymech is a way of ensuring performance from the SPV.

5.9.1 Financial Implications as a Risk Variable

The paymech works by splitting the hospital into functional units. A unit could be the pharmacy, the cancer centre, the cardiac unit or any other hospital zone which serves a specific purpose (or provides a specific function). While each of these zones contains highly critical units such as operating theatres, they also contain less critical units such as offices. The paymech further devolves the hospital from units into functional areas. A functional area is a part of a unit. Devolution of the units allows for more accurate payment deductions to be calculated, should contractual limits be broken.

Such contractual limits include the internal temperature of the space in question, its air changes per hour and its relative humidity percentage. AHUs play a major role in ensuring that the internal environment is maintained at stable levels for both patients and staff. Accordingly, the paymech forms the second half of the risk-based methodology. The failure-event deductions calculation as set out in the MSA has been used as the risk-assignment tool.

$$D(FEs) = \left(\left(\frac{ASPn}{NY}\right) + \left(\frac{VAs}{NM}\right)\right) \times \left(\frac{Nsa}{Ns}\right) \times AWs \times UWs \times DP(FEs) \times Bdln$$

The formula above is the legal method for calculating payment deductions where:

- D(FEs) means the amount (in pounds sterling) to be deducted from the Service payment in respect of the Service failure event.
- ASPn means the Annual Service Payment for the Trust financial year applicable at the time when the relevant Service failure event occurs – this figure has been provided by the Regional Finance Director in an email.
- VAs means Volume Adjustment and has little bearing on the impact of AHUs and their ability to perform. Instead VAs refers more to 'soft' FM services which are not within the scope of the research.

- Nsa means the number of Affected Sessions in the Contract day for each Functional unit. There are three contractual sessions per day which could be affected, these are:
  - 0600 to 1400
  - 1400 to 2200
  - 2200 to 0600
- Ns means the total number of Sessions in a Contract day, provided that, in relation to a Service failure event arising from a failure in the provision of the Managed equipment service, Ns will always equal three (3). These three sessions are noted in point 4.
- AWs means the Area Weighting percentage attributable to the Functional area in which the Service failure event occurs – the area weighting percentages are set out in Appendix 7.
- UWs means the Unit Weighting percentage attributable to the Functional unit in which the Service failure event occurs – the unit weighting percentages are set out in Appendix 8.
- DP(FEs) means the Service failure event Deduction Percentage attributable to the Failure event category allocated to the Service failure event – the failure event categories percentages are set out in Appendix 9.
- BdIn means the Bedding-in period percentage. This is a time-specific variable based on the install and use dates of each respective functional unit. Because the two phases of HCP1 were completed in 2010 and 2014 respectively, the bedding-in time window has passed and so will be given a default value of 100%.

There is an interim-service calculation equivalent set out in the contract; however, because the interim period ends before the completion of this workthis has been ignored. The paymech formula and the risk-based proforma provide a mean risk level for each asset.

5.10 HCP Part Failure Curves – the 'Recommended' Approach

Based on the data collection from the six qualifying hospitals in the study, the following number of failures was recorded:

Table 16: Number of part failures recorded

Part	Failures recorded	No. of parts at HCP1 against 113 AHUs	Part Ratio Part : AHU from HCP1	No. of AHUs	HCPs with recorded failures	Probable number of parts based on part ratios	Failure % to date
Cooling/ Frost coil	24	89	0.787 : 1	299	2-4-6-8	236	10.1%
Heating coil/ Run around coil	20	175	1.548 : 1	261	2-6-8	404	4.9%
Control panel	4	94	0.832 : 1	61	16	51	8.0%
Fan supply/extract	22	128	1.133 : 1	299	2-4-6-8	339	6.5%

Flatbank filter	0	107	0.95 : 1	-	-	-	0%
Other filter	0	14	0.12 : 1	-	-	-	0%
Polyseal filter	0	38	0.34 : 1	-	-	-	0%
Humidifier	5	27	0.239 : 1	176	8-17	42	11.9%
Inverter	48	147	1.300 : 1	256	2-4-6-16-17	333	14.4%
Drive motor	55	181	1.601 : 1	261	2-6-8	418	13.2%
Shut-off damper	4	105	0.929 : 1	140	8	130	3.1%
Silencer (attenuator)	0	142	1.26 : 1	-	-	-	0%
Total	182	1247					

The *part ratio* was determined by counting the number of parts within each AHU in the sample of 113 AHUs at HCP1. This was used to deduce that many parts could expect to be found in an average AHU across the sites used for data mining without physically surveying them. The probable number of parts was determined using this part ratio across the six hospitals. This was as follows:

Table 17: Number of AHUs within each hospital included in study

Hospital	HCP 2	HCP 4	HCP 6	HCP 8	HCP16	HCP17	Total
No. of AHUs	33	38	88	140	61	36	396

The number of AHUs to which the part ratio was applied (above) was dependent on whether the hospital had recorded a failure. If no failure had been recorded, the hospital's AHU count would not impact the part ratio.

Where the failure percentage was greater than zero and less than one, the HCP-Hybrid CDFs were composed of a combination of real data collected from the projects and Monte Carlo simulated data. There were two possible ways of modelling the data:

- **Option 1. A hybrid curve based on the average of the actual and industry curves dependent on the proportion of data –** For example, if you have almost no data, you would opt entirely for the CIBSE simulated curve. If you have a full data set, you trust the data completely. A 50/50 weighting of industry data/simulated data from time *x,* where *x* is the final recorded failure timestep. Prior to timestep *x*, only industry data would be used.
- **Option 2. A hybrid curve irrespective of whether there is a full data set or not –** For example, where *x*% of failures were known to have occurred using the part ratio logic, the remaining percentage could be simulated to create a full distribution replicating the same number of parts as there are in real life.

Option 2 was chosen as representing the truest and most representative profile. Even though no parts had completely failed, the composition of real and simulated data, irrespective of the proportion of failures, meant that the approach produced a smoother profile and reflected the notion that the greater the volume of industry data, the more reliable it became.

There were no recorded failures of silencers; this could be because they are not a rotating or moving part and provide noise protection from the fans inside the unit. Zero filter replacements were observed. This could be due to the fact that the regularity of filter changes means that the cost in time for invoicing and processing the purchase outweighs the cost of the items themselves. In these instances, the Monte Carlo simulated data would be referred to entirely.

5.10.1 Data Analysis

In a bid to ensure data cleanliness, two checks will be used on the collected data prior to extrapolation: the Anderson-Darling test and Probability Plotting. The outcome of these two data analysis methods will be an improved understanding of the sample data.

The Anderson-Darling test is a statistical test of whether or not a data set comes from a certain probability distribution. The null hypothesis is that the data is normally distributed. The p-value is the probability of getting a result that is more extreme if the null hypothesis is true.

Probability plotting has advantages, particularly with incomplete data sets, because it allows analysis to determine if small sets of data come from a normal distribution. Computing the cumulative probability, based on the data available, allows for the z-value to be calculated and plotted against the sorted data (the replacement times collected from the hospital invoices). The coefficient of determination of a linear regression (R^2) will then display *goodness of fit* as compared with the normal distribution. The results of this exercise can be found in section 7.6.1.

5.10.2 Exponential Smoothing

Exponential smoothing in this context can be seen as an additional insurance policy and accounts for data points which are not yet empirical. This will be reflected in the damping factor. There is no hard and fast rule for assigning a damping factor ($1-\alpha$) and the choice of damping factors, under the 'recommended' profile, will be 0.5. The smaller the alpha value, the larger the damping factor and vice versa. A smaller alpha value is likely to smooth out the peaks and troughs of the failure curves more efficiently. It will be a point of research discussion as to which factor is best to use, while ensuring data quality.

5.11 @Risk CDFs

The CIBSE-based replacement curves were created with the intention of providing the same replacement-curve output, allowing a comparison to be made with the HCP data (the result of this will be able to be measured both in terms of replacement proposals and cost profiling).

CIBSE recommends lifecycle replacement as a single point in time; however, regression and statistical manipulation allows for this point to be converted into a distribution curve. CIBSE data is generic in format, rolled up to give yearly estimates based on large amounts of data. For example, a fan may be given a 20-year life expectancy, but CIBSE does not include much more information on how this figure was reached (in what environment, runtime, etc.). There is no single recognisedmethod of assigning a correct distribution. Software exists to enable the correct choice of distribution from a given data set. Commercial computer software can perform Monte Carlo calculations with relative ease, presenting results in simple graphs and tables. These results approximate the full range of possible outcomes, and the likelihood of each. When Monte Carlo simulation is applied to risk assessment, risk appears as a frequency distribution graph, similar to the familiar bell-shaped curve which non-statisticians can understand intuitively (Kirkham, 2002). @Risk was chosen as the tool to run the simulation.

5.11.1 Manufacturers Data and RSL Data Records

The manufacturer's data on AHU components was searched for; however, there was no public information to be collected for the purposes of lifecycle planning and no product declarations or databases were found after a desktop study. Contact was made with McQuay, the manufacturer and supplier of the AHUs on site, but no response was received. O&M information in the form of as-built drawings and inventory spares were obtained for the air-handling units under observation. This allowed a detailed understanding of size and component numbers in each AHU to be formed.

5.11.2 CIBSE Simulated Distributions – the 'Conservative', 'Balanced' and 'Optimistic' Approach Options

Using the cooling coil profile as an example, the following profiles have been created using Monte Carlo simulations of the Weibull, Triangular and Rayleigh statistical distributions.

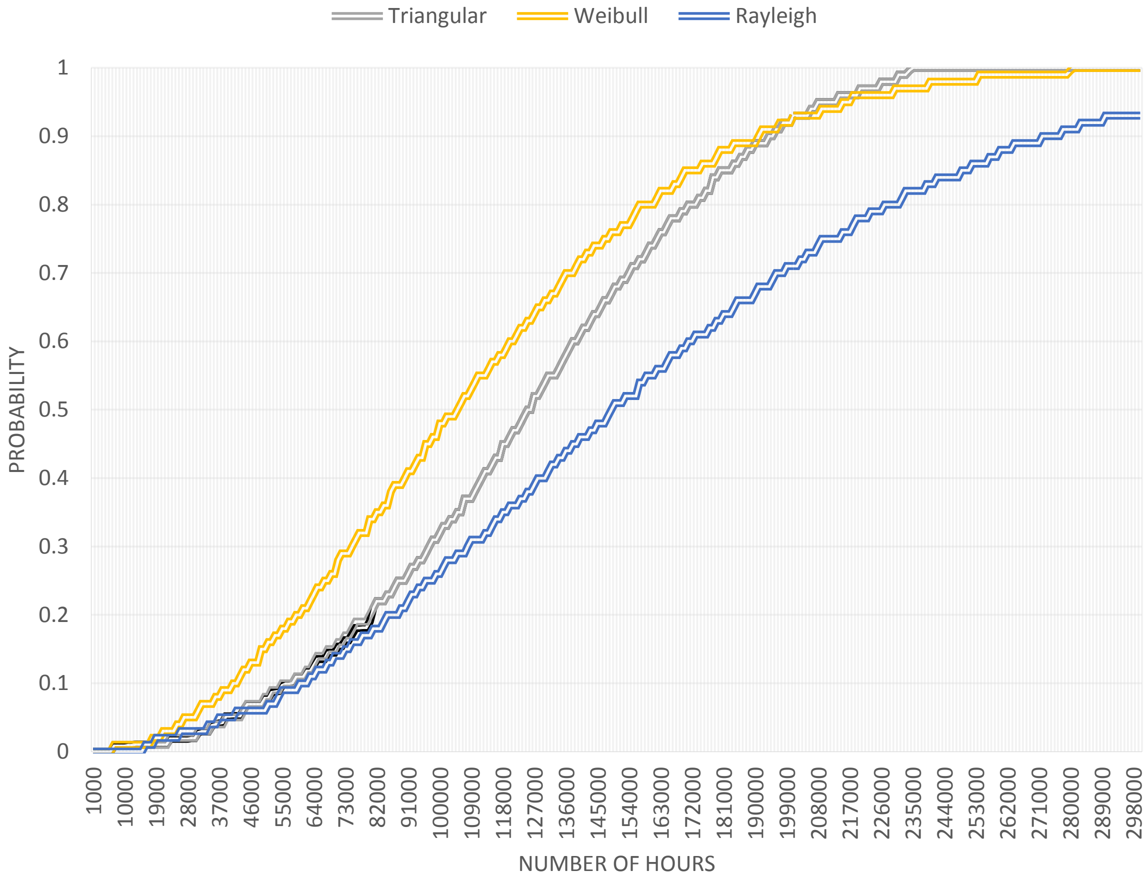


Figure 43: Cooling coil simulated cumulative density functions

The Weibull distribution is largely recognised as being the truest representative of failure and it is this distribution that forms the basis for the Bathtub curve and its three phases.

The macro-fixed variables across all CDFs were:

- **Lifetime** – CIBSE Guide M recommended lifetimes for each part (see Figure 40)
- **Runtime per day** – assumed to be 22.9 hours

The micro variables in generating each of the CDFs were:

- **Triangular distribution** – minimum life (first recorded failure from HCP data, 0 in the case of silencers), mean life (runtime per day according to CIBSE x lifetime), maximum life (mean life + difference between first recorded failure from HCP data and CIBSE lifetime)
- **Weibull distribution** – alpha (2 for all parts save control panel which was set at 5), beta (runtime per day x CIBSE lifetime)
- **Rayleigh distribution** – beta (runtime per day x CIBSE lifetime)

Table 18: Distribution risk levels for lifecycle model decision-making ability

Distribution	Decision-maker risk appetite level	Risk level
Rayleigh	'optimistic'	High
Triangular	'balanced'	Moderate
HCP Hybrid	'recommended'	Moderate
Weibull	'conservative'	Low

The Monte Carlo simulation was run over 100 iterations for each part. The results will be discussed in the next chapter.

5.12 The Lifecycle Model

Table 19: Model overview aspects table

Model aspect	Description
Responsibility matrix / maintenance cap	All works containing geometry and above the maintenance cap of £1,000 (excluding HEPA filters)
AHU's start-life date	01.01.2010 (Phase 1) and 01.01.2014 (Phase 2)
Inflation	8 indices available to user (from BCIS database)
Financial smoothing	Not included in model
Failure-distribution data	Both HCP Hybrid and @ Risk CDFs included
Geometry	Only items included in the LoD of the geometrical model will be included
Mean runtime	Assumed to be 22.9hrs/day, 7 days per week (based on HCP1 phases 1 and 2)
System nomenclature	NRM3

5.12.1 The Responsibility and Definition of Maintenance Works

The definition of maintenance works as set out in the HFM contract between the SPV and HFM subcontractor encompasses any works for maintenance or repair of the Facilities that are necessary to ensure that the Facilities are maintained in accordance with the Service Level Specifications, the Interim Service Level Specifications and the Method Statements for the Estate Management Service. The definition also requires that the Facilities comply with the Trust's Construction Requirements and Project Company's Proposals (including, without limitation, the renewal or replacement of any Plant or equipment) throughout the Project Term.This definition does not explicitly delineate lifecycle, and instead describes maintenance as an all-encompassing activity in supporting the upkeep of the facility. The definition does not discriminate in terms of risk holding.The definition does not distinguish between maintenance and lifecycle. Instead, Schedule 28 (28.22) of the Hard FM Contract states:

If, in circumstances other than an emergency, the need arises for Unprogrammed Maintenance Work (which includes any Reactive Maintenance Works) (excluding any works of a de minimis nature which, for the purposes of this Clause 28 shall be deemed to be works of a value of less than £1,000 per incident adjusted in accordance with RPI at the beginning of each Contract Year) in respect of which the Parties *and the Trust have agreed this Clause and clause 28.8 of the Project Agreement shall not apply, the Hard Services Provider shall not carry out any Unprogrammed Maintenance Work (which includes any Reactive Maintenance Works) unless and until:*

- *28.22.1 pursuant to clause 28.8 of the Project Agreement and paragraph 3(h) of schedule 10 to the Project Agreement, the Trust's Representative has approved the proposed commencement date, the proposed hours of work and estimated duration of the requisite Unprogrammed Maintenance Work (which includes any Reactive Maintenance Works). The Hard Services Provider shall be responsible for obtaining the Trust's approval and shall for that purpose prepare and submit, on behalf of Project Co, all necessary proposals relating to Unprogrammed Maintenance Work (which includes any Reactive Maintenance Works), pursuant to clauses 28.7 and 28.8 of the Project Agreement and in accordance with schedule 10 thereof; and*
- *28.22.2 Project Co and the Funders' Technical Adviser have approved any Reactive Maintenance Works and the costs thereof.*

In Layman's terms, clauses 28.22.1 and 28.22.2 mean that the HFM team may not proceed with works unless:

- The trust has approved the work.
- Project Company and TA have approved the costs.

It is to reflect Schedule 28 that only reactive maintenance and unplanned maintenance works have been considered in the model. Essentially, the works have been unforeseen and therefore these data points represent the true end of life for each component part. Perhaps most crucially, the contract does not strictly delineate between the parts of the equipment which is the HFM team's responsibility and the parts which are the responsibility of the SPV (defined as a responsibility matrix). There is no responsibility matrix associated directly to AHUs at HCP1. Instead, £1,000 (otherwise known as the *reactive maintenance* cap) rising by RPI, is stated as the baseline figure which separates maintenance and lifecycle. It is this figure that will be included in the model, and all recorded parts with a cost below £1,000 will be ignored and deemed as maintenance.

5.12.2 The Start of the AHU's Life

There is some conjecture as to which date provides the best footing for the lifecycle model. The dates were as follows:

- Hospital commissioning date – the date the hospital was commissioned could be used; however, because the equipment will have been installed and tested prior to operations, it may not provide a true picture of the actual hours run. Instead, it may skew the figures to look like the AHU had been running fewer hours to date than had actually been the case. It is a rose-tinted take on the number of hours run to date, and therefore will not be used.

- Site-install completion document – this document specifies the date when each AHU was installed. It is a good guide, but because the units will have been installed over a period of time, and this could be the beginning, middle or end of the project, depending on the construction programme, it may not be the best indicator. It may prove useful if the key damage mechanism being recorded was corrosion or other environmental concerns relating to the physical degradation of materials. However, because the key damage mechanism is used over time, this may not be the best date to use as install-completion documents are often signed over prior to the AHU's connection to ductwork and lagging (i.e., prior to its operation). An example of a site-install completion document for one of the AHUs at HCP can be found in Appendix 10.
- Pre-commissioning date – the pre-commissioning date could perhaps be more accurate than the previous two because it is the date when the lagging, ductwork and other aspects of the AHU (pertinent to its operation) were installed.

The pre-commissioning dates for the AHUs were deemed to be the best indicators of their runtime to date. These dates were chosen for their ability to concatenate the two phased facilities into two base dates for their AHUs, enabling a clearer understanding of the model in future

5.12.3 Failure Distribution Data

The AHU replacement distribution-modelling sheet was built to view the replacement data and identifying any faults. The model is binary-based and macro-enabled to allow for easy navigation, data input and manipulation. The model contains tabs for each individual component and is detailed in the part-failure curve tab. Each curve feeds forward to allow top-level viewing; however, the data for each component sits within its respective tab. Appendix 11 illustrates the AHU replacement-curve model's component tab, which is replicated for each component respectively. There are six major aspects to the component's tab sheet. These are as follows:

Table 20: Part replacement curve model - component tab descriptions

Label	Description	Dependency
A – Part-ratio calculator	Calculates the number of parts expected on site based on the number of AHUs (according to ratios discussed earlier in the chapter)	External data
B – Probability calculator	Considers aspects such as the number of failures as well as when they occurred. Outputs numerical PDFs and CDFs	A,C,D

C – Replacement Data input	Calculation of estimated service life based on part installation, replacement date and weekday/weekend runtimes. Outputs and hours to replacement figure for each recorded replacement figure.	External data
D – Binary-hour viewer	A visual checking process to ensure data correctness and avoids data duplication or manual input errors	C
E – Cumulative density-function curve	A visual profile to help estimate the replacement performance of each part, over time.	A,B,C,D
F – Tab bar	A navigation bar for the user. Allows easy navigation between part-specific replacement data and CDF visual-profile overview tab.	N/A

As can be seen from the table above, A and C are dependent on external data. On receipt of this data, the replacement curves can be created, forming a functional output on which replacement decisions can be based. This output is fed forward to the lifecycle model

5.12.4 Financial Smoothing

Financial smoothing has been ignored in the context of this work.

5.13 PALM Visual Modelling Stages

This section outlines the stages involved in creating the lifecycle visualisation tool and discusses the stages shown in red in the PALM architecture diagram.

5.13.1 The BIM Model

HCP1 contains an existing BIM model. Skanska, the company behind the initial construction of HCP1, were the owners of the BIM model and had commissioned the creation of the model to aid in their construction processes (due to the utilisation with common construction hurdles such as clash detection). During the transition from the facility's construction to operational life stage, the SPV and HFM teams were appointed, with Skanska FM running the hard operations. When approaching the SPV Estates Director the model was retrieved; however, it was only available to the SPV Estates Director and, subsequently, to this research as a read-only model. The model comprised of individual .NWD files, so the read-only model was extracted and converted into a .3dm file which would be more malleable to computational adaptation. Prior to building the heat map, a data conversion and cleansing exercise had to be undertaken prior to building the model. The data-cleansing exercise consisted of the following steps, as illustrated in Figure 44:

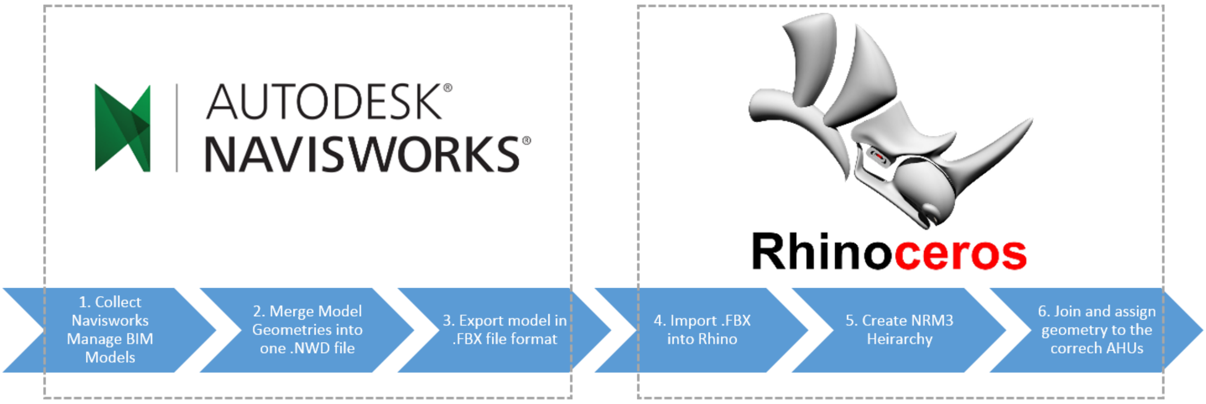


Figure 44: Data transfer flow diagram from BIM model to Geometrical model

- Step 1. The models were collected from the HCP1. The model was split into 72 separate .NWD files ranging in size from 23kb to 50mb.
- Step 2. The models were imported into one common file which. The reason for the merge was to ensure that all the case study components, which might be needed for the heat mapping, were captured. It also allowed for future planning should a similar analysis be undertaken on other assets.
- Step 3. The newly combined Navisworks file was then prepared and exported into .FBX format.
- Step 4. The .FBX file was imported into Rhino in mesh format.
- Step 5. The NRM3 hierarchy was created to ensure efficient ordering of the model.
- Step 6. The geometry of the AHUs was identified and the remainder of the model was stripped away, reducing the file size. Once the AHUs had been identified, a separate process of analysing the O&M data and assigning the meshes to the NRM3 hierarchical structure was undertaken.

The outcome of this process was a model which had been structured according to NRM3 with each subcomponent assigned. This made for an informative user interface and a benchmarked method of structuring the data. Figure 45 below illustrates an example AHU (AHU 36S) and how the user can view the geometry of the components. At this point, there is no data being channelled through the geometry. Figure 45 exemplifies a data-cleansed AHU consisting of a 1-mesh-per-component make-up and an individual assignment of each mesh within the NRM format.

As discussed during the literature review, cases II and II in the diagram of Figure 46, below, apply different design approaches on the understanding that the building has already been constructed. Previously, it was a question as to whether an existing BIM model was available. But with the existence of a redundant model at our disposal, an update of pre-existing BIM (path 2) was used as the path of model creation.

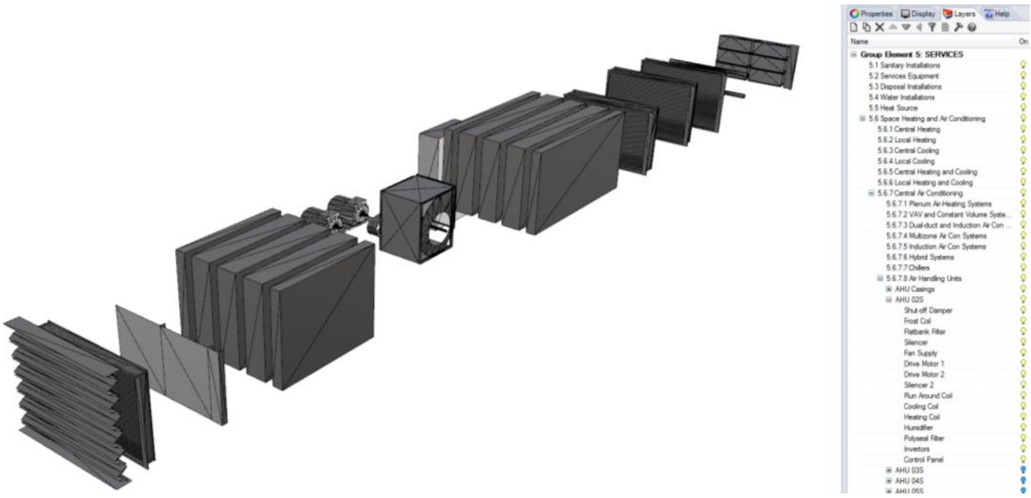


Figure 45: AHU components (left) and NRM3 hierarchy

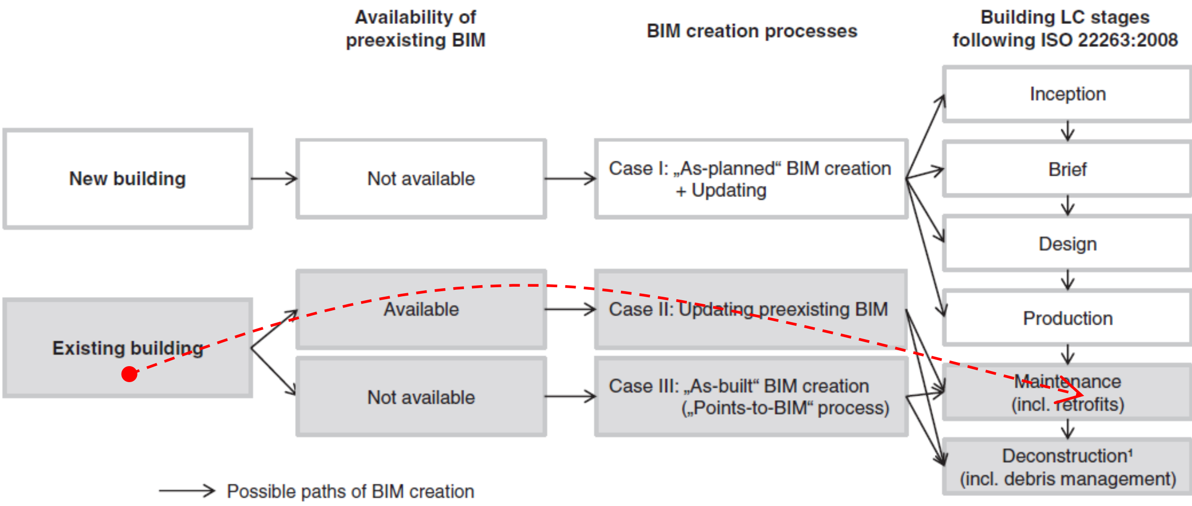


Figure 46: Possible paths of BIM creation and chosen path based on BIM availability

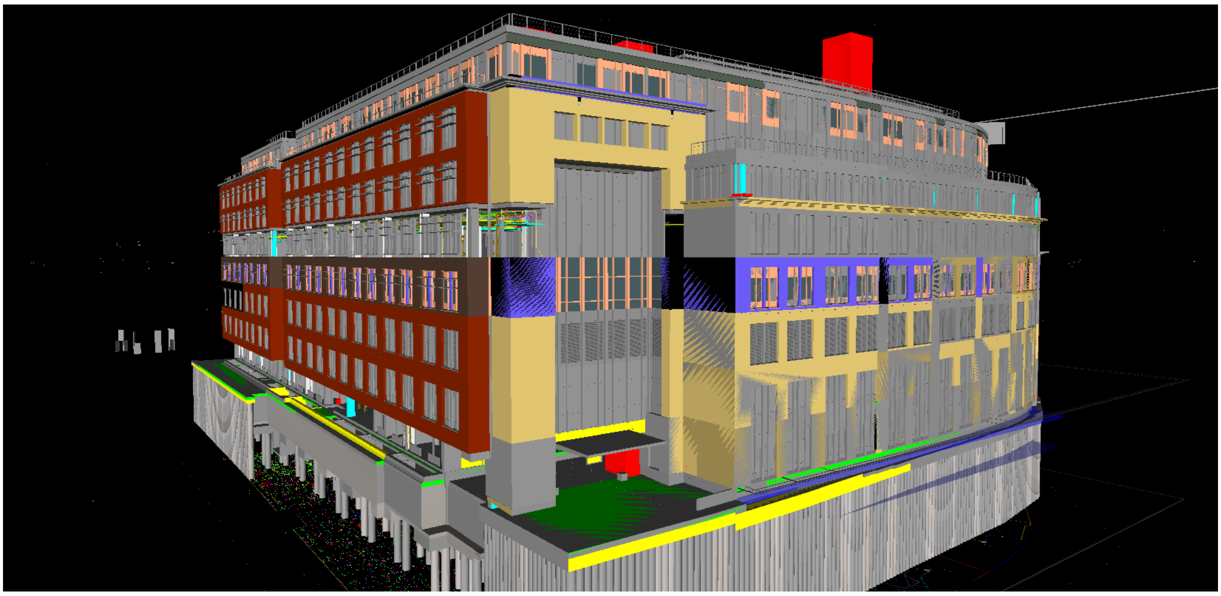


Figure 47: The Assembled model ready for import

5.13.2 The Geometrical Model

Figures 48, 49 and 50, illustrate the AHU model (including the ductwork system excluding the casing, with all the components exposed).

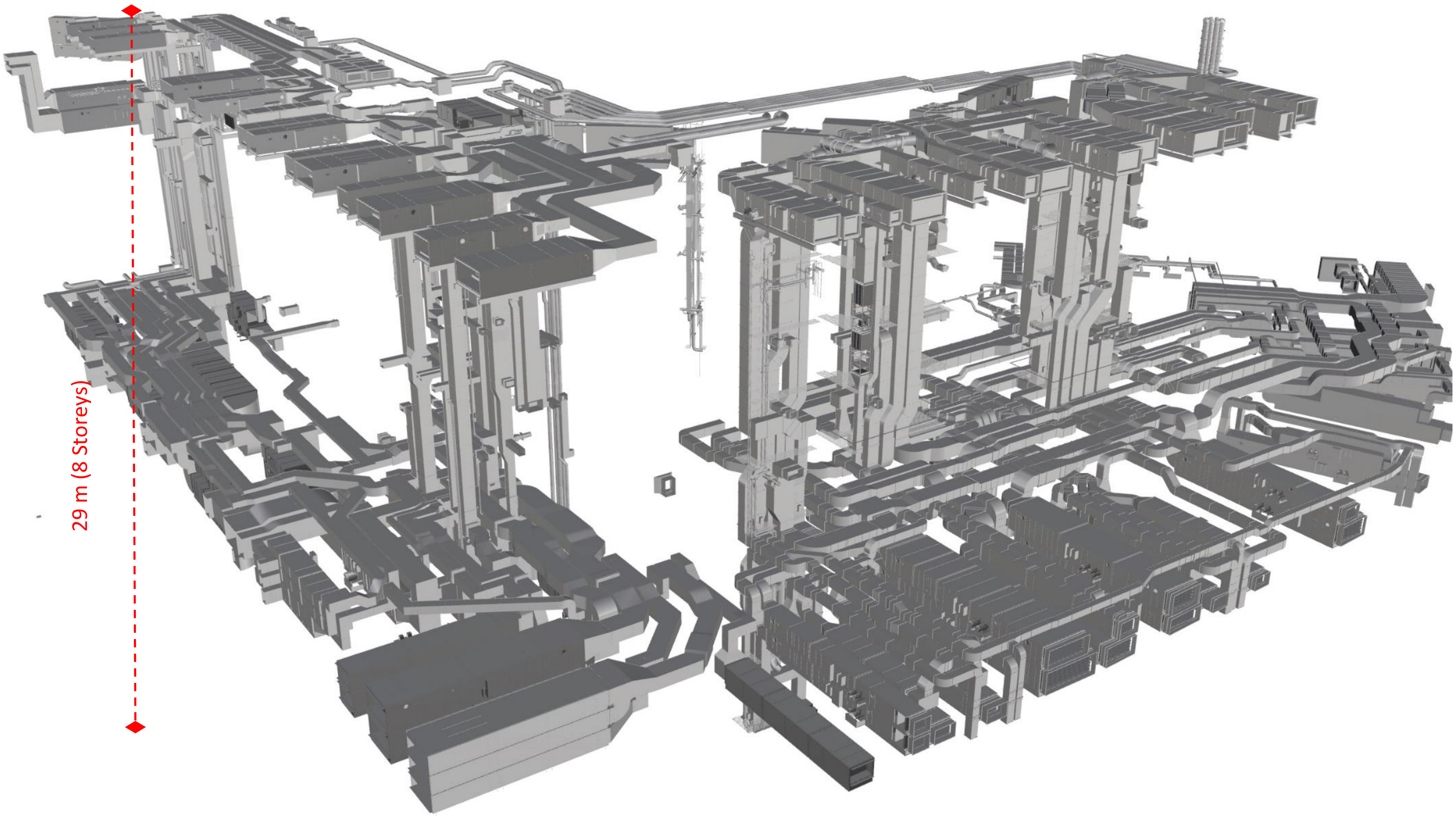


Figure 48: HCP1 Air-handling unit geometrical model including ductwork and casing

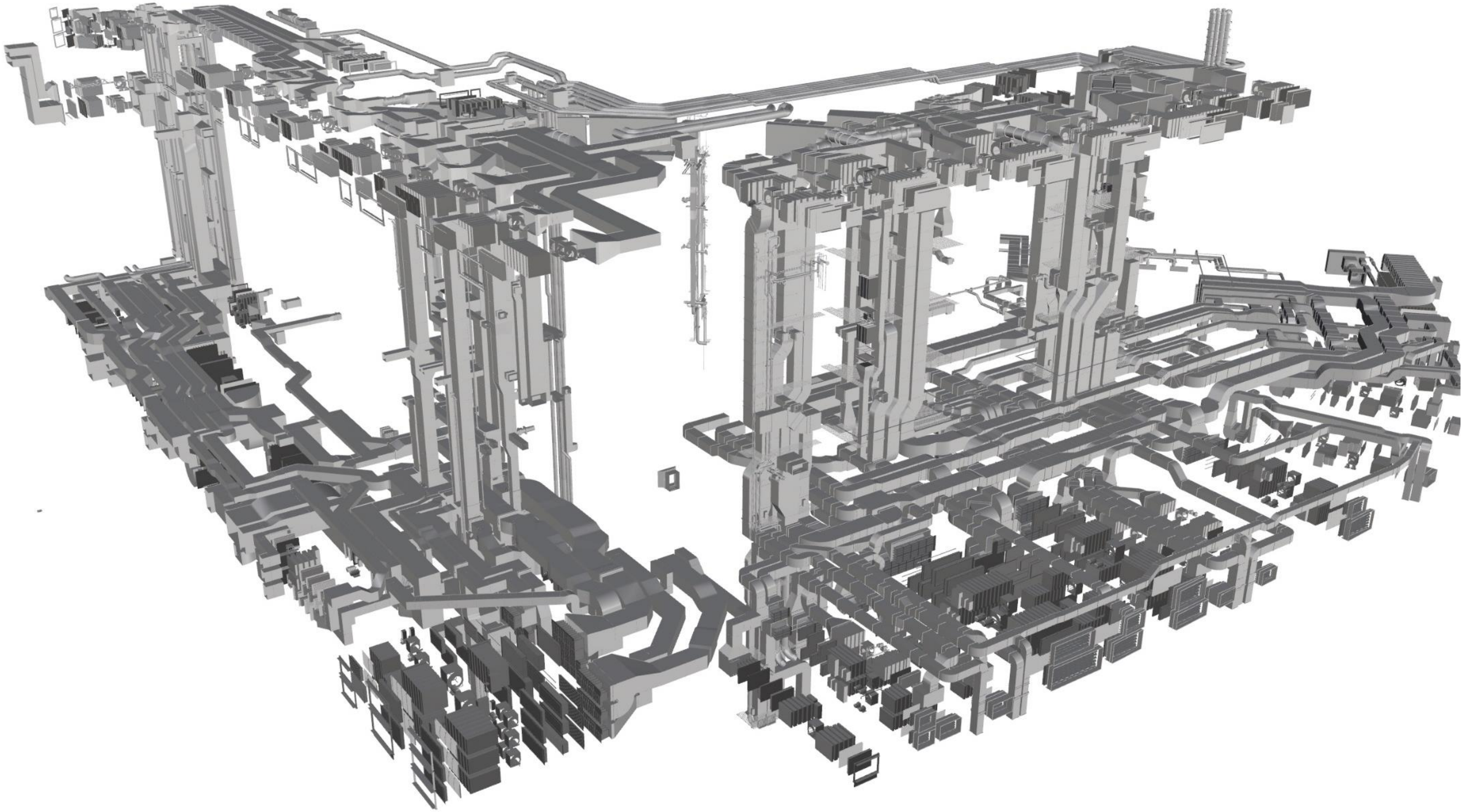


Figure 49: HCP1 Air-handling unit model including ductwork and excluding casing

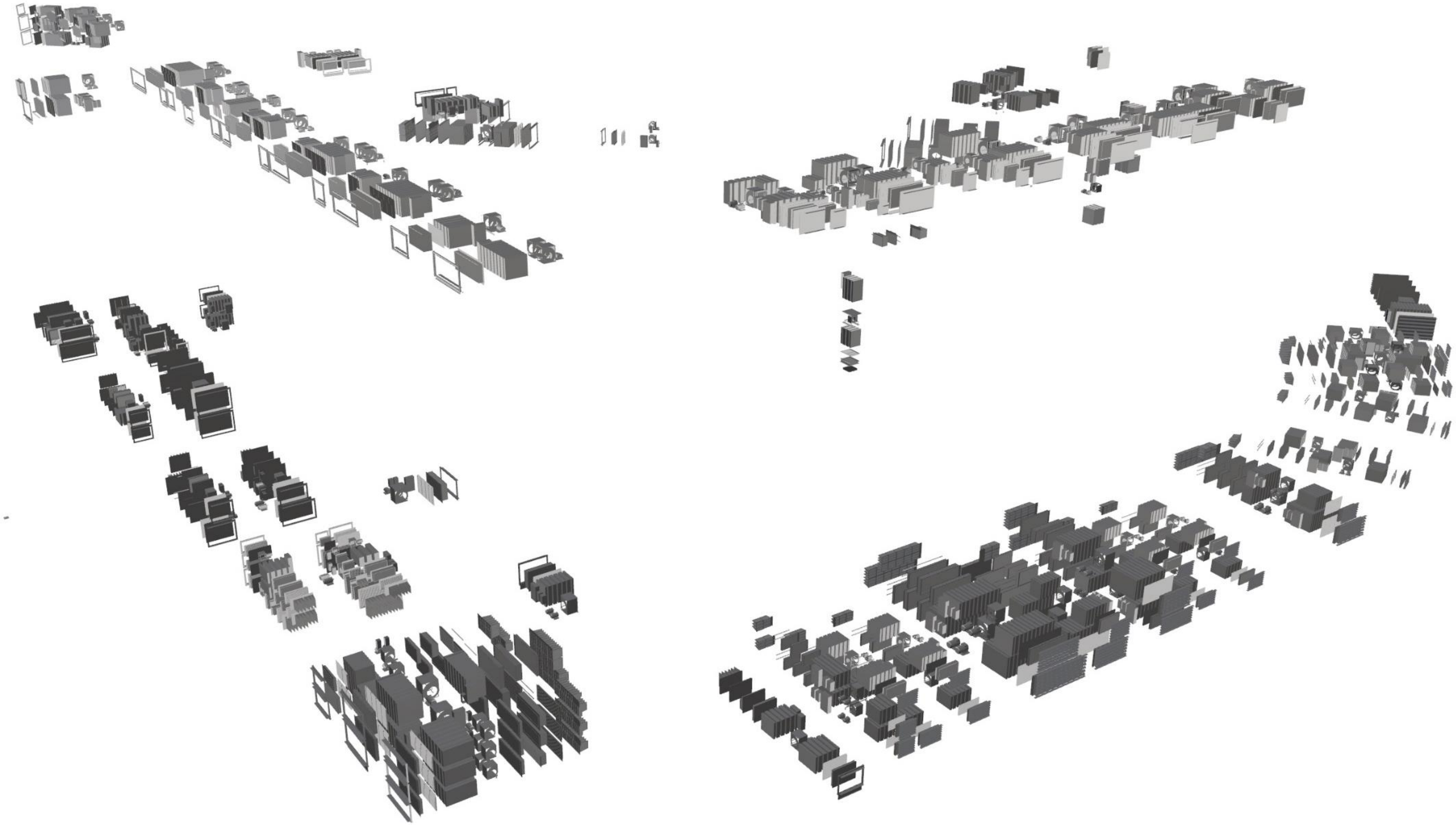


Figure 50: HCP1 Air-handling unit geometrical model inclusive of 1,247 components

The following AHUs were missing from the model:

- AHU47A Supply (6th floor)
- AHU47B Supply (6th floor)
- AHU48 Supply (6th floor)
- AHU DE01 (7th floor)

5.13.3 3D Heat Mapping

The 3D Heat Map modelling was an iterative process consisting of an initial data cleansing exercise prior to building the heat-map logic. Based on the understanding that a 3D Heat Map is calibrated correctly, it can quantitatively display the predicted condition of the plant employing a basic stakeholder graphic using schematic colouring, making the tool intuitive to use. The ultimate aim is to show the asset condition, through the use of colour, on a three-dimensional level through the course of time.

The model and its development will be discussed as a series of steps, taking an iterative process of building based on the understanding that:

- It is a client-focused tool
- It considers real-world issues involving contractual levers
- It is an iterative process of joint inquiry between stakeholders

The AHU-Level Visualisation is a direct output from the physical condition survey. The resulting risk level has been assigned to the geometry with red equalling high risk and green equalling low risk. The visualisation progresses through an RGB colour gradient and maps the risk values to correspond with their respective colours. E.g. red = 255, 0, 0 and green = 0, 255, 0 (Figure 51).

The purpose of the AHU level visualisation is two-fold. Firstly, at a glance, it allows decision-makers the opportunity to see which assets are at a higher risk of failure than others. Secondly, it informs the replacement decision for each of the respective subcomponents it houses.

The Component-Level Visualisation is fed data directly from the survey results. This level allows decision-makers the opportunity of seeing the condition of the parts at any given point in time throughout the concession period. The visual-degradation mechanism is based on the same principle as the AHU level (as seen in Figure 52).

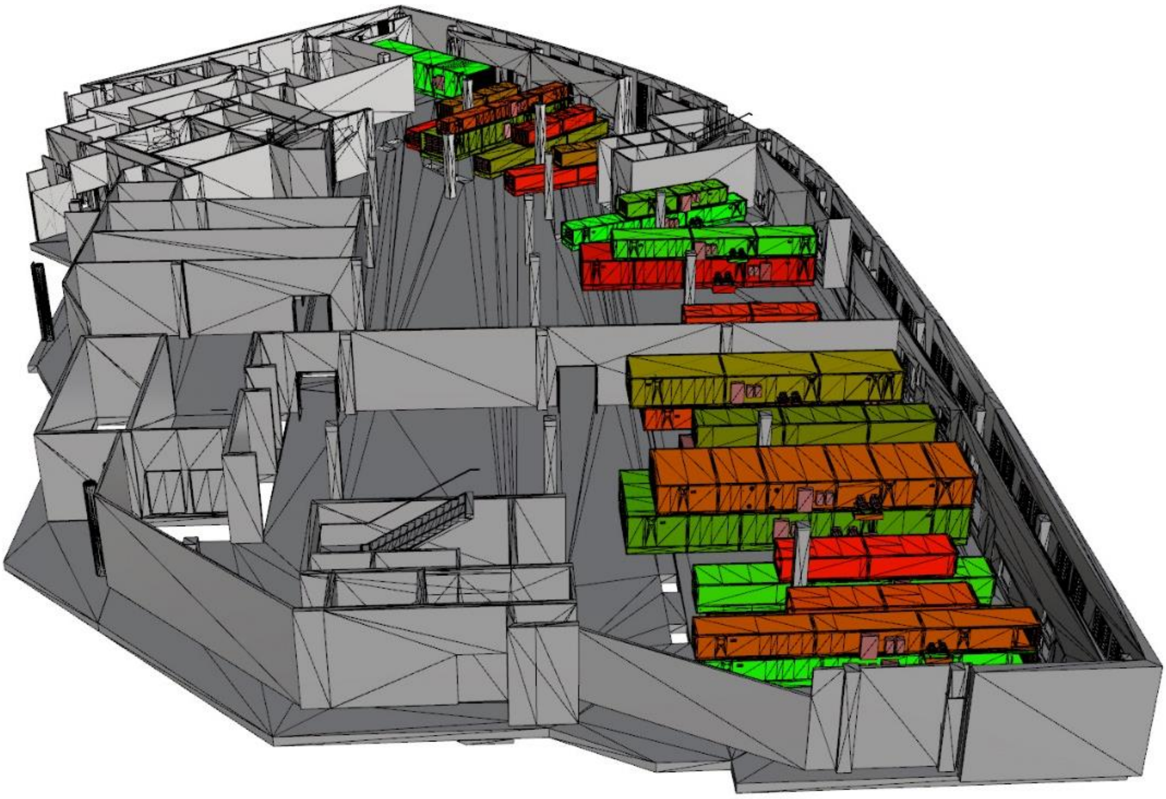


Figure 51:2nd floor plant room AHU risk level visualisation

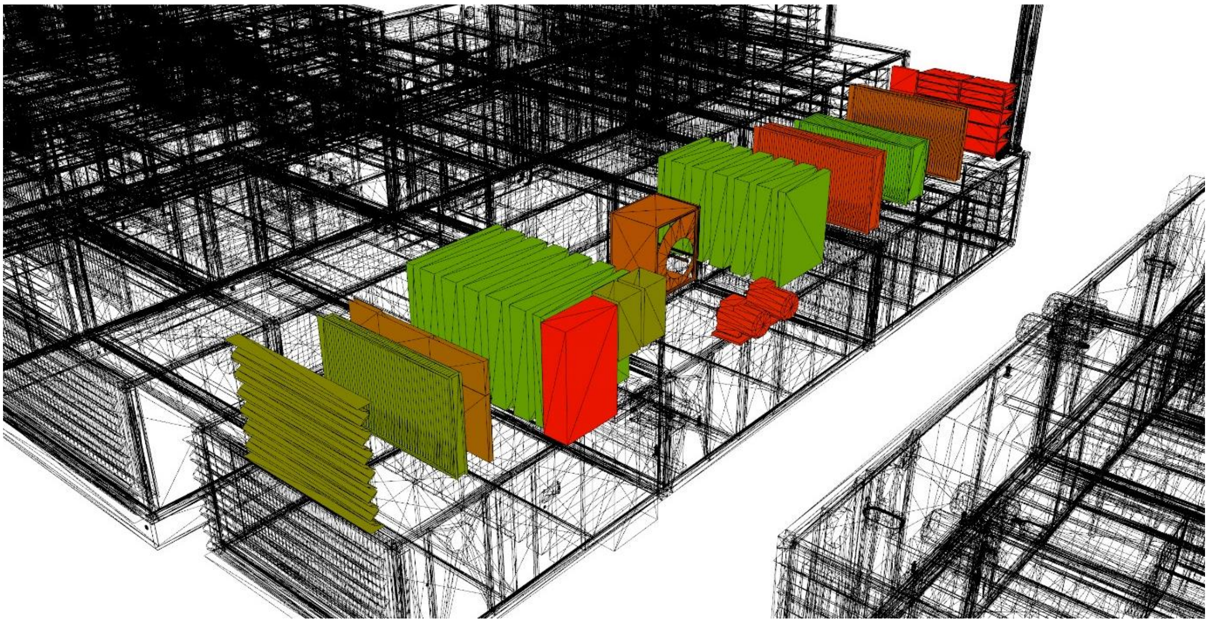


Figure 52: Component level condition view -AHU 36S

As can be seen above, each component has a different colour associated with its geometry. This level of detail is currently unseen in operational lifecycle modelling, and with this level of detail that a better degree of interrogation for proposed future replacement works can be put into practice by decision-makers and impartial advisors. Essentially, the degradation value of each unique part is based on the risk level for the AHU and the replacement curve based on the data collection. With each curve being different, it means that each component has a different lifespan.

5.14 Computational Engine

The Grasshopper engine has been built using a three-layered system:

1. First layer: User interface
2. Second layer: Code blocks
3. Third layer: Code logic

5.14.1 The User Interface

The user interface (or control panel) is the upper level of the Grasshopper model. At this stage the model is assumed to be complete and it allows the user/decision-maker to interrogate and query the model and receive outputs in real time. The user interface will display the following information and data streams:

- ***The year slider*** – the viewer can adjust the year to generate real-time outputs from the model.
- ***The year-in period*** – the time at which the model is being viewed to corroborate the lifecycle model with the visual model and draw conclusions.
- ***Stream 1*** – AHU System Risk level viewer – the viewer can switch this viewport on to review the visual output of the condition survey. The view will hide the components but reveal the AHU-casing geometry where the risk level will be visible.
- ***Stream 2*** – AHU System Component replacement viewer – the viewer can switch this viewport on to review the visual output of the lifecycle model replacement proposal. The view will hide the AHU-casing geometry and reveal the components housed within.
- ***Stream 3*** – AHU Gradient Stream replacement viewer – this viewer is identical to stream 2; however, it displays the components on a colour gradient..
- ***Stream 4*** – AHU System Component unit-cost viewer – this viewport is an interrogation device for the asset manager/quantity surveyor for tracking the level of unit-cost associated with the component. Green equals little to no unit-costs and red indicates high unit-costs.
- ***Streams 5 & 6*** – AHU System Component Base and Net cost viewer – these viewports allow the user to understand the cost implications of the lifecycle model in real and nominal terms.

- *The Colour Key* – Included in the user interface, this tells users what the model is saying whenever they select one of the six viewport streams.

5.14.2 The Code Blocks

There are two code blocks: the AHU code block and the component code block, both of which contain packaged Grasshopper logic. Their purpose is to act as an easy user interface for the model builder. The packaging of the logic means that the modeller does not have to deal with the minutiae of the logic and can instead build their Excel lifecycle model as usual and 'plug' the data in. In terms of user expertise and future proofing, it does not put pressure on an organisation to ensure that future modellers have a high level of visual modelling skills as a prerequisite for being employed. The AHU-code block is directly connected to the Excel-based model and receives inputs including sheet number, source and target data and survey-risk levels. The component code block receives geometrical input in the form of mesh linking to Rhino.

5.14.3 The Code Logic

The Code Logic is nested within the AHU code block and facilitates the six data streams. The different streams require different data manipulation to achieve the required result. The logic diagram for Stream 1 is shown in Figure 53.

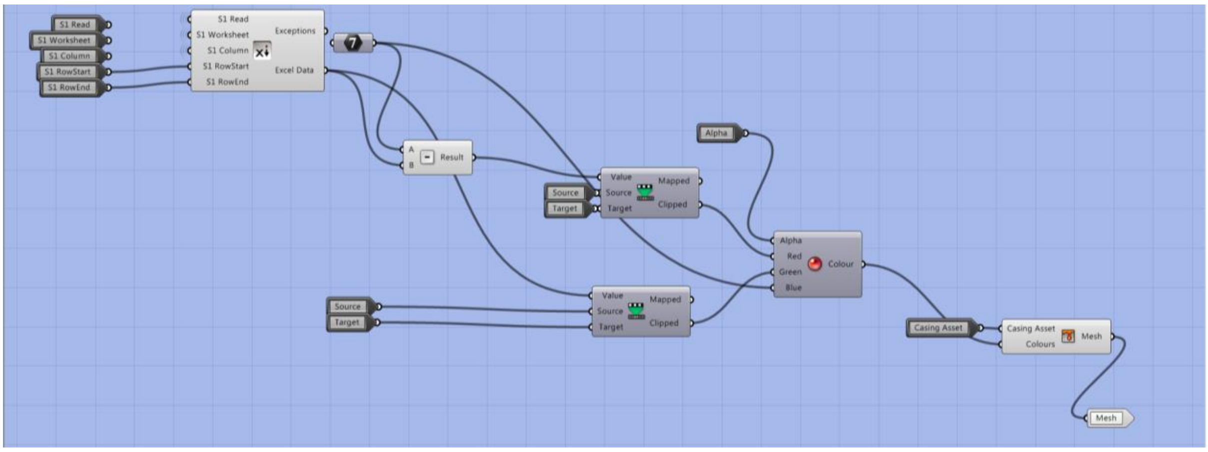


Figure 53: Stream 1 logic diagram

Stream 1 receives the Excel life cycle model as an input as well as source and target mapping data. Based on the limits of the data, the source and target inputs map the values to create the colour spectrum. This colour feeds forward and is assigned to the appropriate casing asset input geometry. The merging of geometry and data occurs prior to outputting the mesh to the model. The logic diagrams for streams 2-6 can be found in Appendix 12. A summary of the data streams inputs and outputs can be seen in the table below.

Table 21: Data stream inputs and outputs

Stream	Inputs	Outputs
Stream 1: AHU System risk-level viewer	• Stream toggle • Lifecycle model – lifecycle worksheet • AHU-Risk level • Lifecycle model row start • AHU-casing geometry	System level visualisation
Stream 2: AHU System Component-replacement viewer	• Stream toggle • Lifecycle model – RGB lifecycle worksheet • Unique component list • Lifecycle model row start • AHU-component geometry	Component level visualisation
Stream 3: AHU Gradient Stream-replacement viewer	• Stream toggle • Lifecycle model – lifecycle worksheet • Unique component list • Lifecycle model row start • Component quantities in system • AHU-component geometry	Component level visualisation
Stream 4: AHU System component unit-cost viewer	• Stream toggle • Lifecycle model – lifecycle worksheet • Unique component list • Unique component cost • Lifecycle model row start • Component quantities in system • AHU-component geometry	Component level visualisation
Streams 5: AHU System total cost during concession	• Stream toggle • Lifecycle model – lifecycle worksheet • AHU total cost in concession • Lifecycle model row start • Component quantities in system • AHU-casing geometry	System level visualisation
Streams 6: AHU System total cost during handback	• Stream toggle • Lifecycle model – lifecycle worksheet • AHU total cost in handback • Lifecycle model rowstart • AHU-casing geometry	System level visualisation

5.15 Tool Testing

The tool will not be validated during this research. The true validation of PALM would be an exercise over a far longer timescale and would involve the reviewing of the financial predictions as well as the level of uptake on the visual modelling approach. Instead, testing of the tool will been undertaken in two ways.

- Option Testing – this will involve the comparison between the financial profiles produced and the current funding profile for the air handling units. The option test will allow the benefit of a component level life cycle model to be illustrated through area charts and will be fiscally presented using the standard life cycle costing metrics as stated in Table 2.

- User Testing – this will involve real stakeholders from HCP having the opportunity to see and use the tool during their December board meeting. Following this, a series of interviews will be undertaken to gauge the users experience of the PALM visual modelling tool.

5.16 Summary

This chapter has presented the method for the construction of the Physical Asset Lifecycle Model. The research environment, objectives and nature were considered in selecting the appropriate methodology which fed the model within the context of the built environment to which it is to be applied. The PALM methodology is based on an amalgamated understanding of the subject area through undertaking the literature review.

The built environment has been dominated by a plethora of quantitative-based research, and this methodology is of a similar ilk. Consisting of statistical modelling, cumulative distributions and geometrical extractions from read-only BIM models, this research presents a wholly deduced quantitative approach. The approach differs from the generic industry approach in two key areas:

- An increase in reliability, transparency and a scientifically rationalised justification for the proposed asset lifecycle model.
- A tool which bolsters investors' decision-making abilities.

Both of these differences are achieved through collecting new data and through breaking the asset down into its component parts rather than following CIBSE's recommended 25 and 20-year lifetime cycles for the AHU asset as a whole. The latter part of the chapter disclosed the practical method of how the model will be built:

- HCP 2-18 data
- CIBSE Lifetime data
- Asset register data
- Engineering-risk survey
- Financial-risk formula

Key issues to be taken away from this Chapter are:

- The decision-making capabilities which result from creating optimistic, balanced and conservative risk profiles are based on the simulated and real data.
- The life cycle model feeds datato the visualisation element of the geometrical model. The geometrical model is made up of extracted .NWD data and an underlying computational engine which draws the data from the Excel life cycle model.

Chapter 6. Results

6.1 Introduction

At this point the research objectives from Chapter 1 should be revisited. These are:

- To create a model building approach based on a detailed understanding of the PFI business model and context.
- To develop a model to improve using the necessary factors to achieve the solution.
- To build a model that can be translated and expanded to other projects in future.
- To qualitatively collect and analyse feedback from stakeholders in the position of approving lifecycle works.

PALM aims to integrate operational lifecycle modelling and geometrical visualisation techniques to provide an improved decision-making tool with regard to AHUs in a case study hospital building. This chapter will discuss the results of the various components within the PALM architecture diagram. These being:

- Engineering risk-survey results
- Financial risk implications of the failure of each AHU
- Monte Carlo simulated CDFs
- HCP UK hybrid CDFs
- Part costs
- Geometrical model's impact on decision-makers

The geometrical model's impact on decision-making abilities will be determined by demonstrating the tool to the HCP Management Board and assessing their views.through interviews.

6.2 Engineering-Risk Survey Results

An example of the risk-survey results can be seen in Figure 54 below (AHUs 01E to 11AE). The X-axis denotes the AHU and the Y-axis denotes the risk level based on the outcome of the proforma risk survey input. The remaining graphical outputs can be found in Appendix 13 (11AS to DE05). There are three sets of results which have been profiled along the Z axis, with one surveyor either side of the average which sits in the middle. It is the average figures which will be used in the final model and analysis, as they provide a median view of both surveyors' professional opinions. The back wall and side wall show the colour gradient, denoting lower percentages as being risky assets (based on the seven pro-forma factor categories) and the *higher percentages* being *less risky*. Overall, the upper and lower risk limits for the model were 82% (AHUs 02S, 06S and 23AS) and 11% (AHU 30E) respectively. The AHUs have been profiled numerically (as is the case with the lifecycle model and NRM3 structure in the geometrical model) and the results will be discussed chronologically.

6.2.1 Air-Handling Unit 01E to Air-Handling Unit 11AE

Graph 1 (in Figure 54) displayed a local maximum of 82% (AHU 02S) and minimum of 12% (AHU 04E). AHU04E was seen as particularly risky and factor category B (Design level) was assigned as 'very high' by both surveyors. This was noted as being due to the lack of access to the AHU because of extensive working platforms which block access doors to the internal components of the AHU. The outdoor environment made little impact on the risk level but the maintenance level was marked as an aspect of risk. There was water pooling on top of the AHU where previous maintenance had been carried out and presumably a workman walking on the unit had caused dents in the ceiling panels which then allowed water to pool. The surveyors' evaluations of the AHUs seemed fairly consistent, with Mr Skanska perhaps being slightly the more reserved in some cases (AHUs 05AE, 05BE and 06E) where he assigned a visibly higher risk than Mr HCP. This may be due to the fact that as an operations manager on site, he is more aware of the risks these assets pose. The jagged fluctuations in the curves which are consistent across all three profiles can be accounted for by the mounting of the AHUs. Internally mounted AHUs scored circa 11% statistically lower-risk levels than their externally mounted counterparts. The majority of the extract units were mounted on the 8th floor (roof) with the exception of AHU 10E.

6.2.2 Air-Handling Unit 11AS to Air-Handling Unit 17BS

Graph 2 (in Appendix 13) displayed a local maximum of 80% (AHU 12S) and minimum of 26% (AHU 12E). There is no variance between AHUs 11AE and 11BS, because these AHUs were part of the ongoing construction works and were assigned a mean risk value of 62%. Post completion, it is envisaged that these AHUs should be resurveyed to ensure they have the correct risk rating. The surveyors were less consistent in terms of their views on the risk of the assets, as can be seen from the profile from AHU 15AE onwards. AHU 15BS is a pertinent example of this with Mr HCP assigning a risk rating of 73% to Mr Skanska's 59%. The difference was predominantly due to a difference of opinion around the usage-conditions factor category, with Mr Skanska being more critical of the use of the asset. He also noted in the comments section of the proforma that there was a 'steam leak on pd impulse line' which may have swayed his opinion. While not a dramatic problem at present, it does indicate intensive usage and a weak spot in the copper due to bending of the pipework

6.2.3 Air-Handling Unit 18E to Air-Handling Unit 28AE

Graph 3 (in Appendix 13) displayed a local maximum of 82% (AHU 23AS) and minimum of 15% (AHUs 27AE and 27BE). AHUs 27AE and 27BE are both located towards the south of the 8th floor, and both were scored identically because of their positioning on the roof. While access was seemingly readily available, the doors to maintain and inspect the equipment were hard to access. Also, the lack of shelter from other units or coverings (being single-stacked units) coupled with high exposure to prevailing winds and other external agents due to the design of the building, meant that the design-level criterion was considered a particular risk for both assets. AHUs 20S to 24S scored similar risk ratings. The reason for this is their location within the facility. All of these units, whether supply or extract, were located internally on the second floor of the facility. The surveyors examined these units on different days, as they are located across both phases one and two of the facility. However, their differences of opinion on the units only varied as to the stack position, with middle-stacked units scoring a slightly higher risk rating due to increased access needs. None of these AHUs were part of a triple-stacked installation setup.

6.2.4 Air-Handling Unit 29S to Air-Handling Unit 39S

Graph 4 (in Appendix 13) displayed a local maximum of 80% (AHU 23AS) and minimum of 11% (AHU 30E). AHU 30E, an extract unit located towards the north-east side of the 8th floor roof, is considered – on average – to be the technically most susceptible to failure and replacement, and therefore the most risky. Its design level, work-execution level and maintenance levels were all considered at least a 'high' and took up 12 out of the 17-year span to which the surveyors were allowed to assign the risk-exposure factors. The unit displayed poor access levels, signs of fatigue, dented casing and a distinct lack of space for manoeuvre because of adjacent restrictions and a working platform which almost encircled the asset at mid-level. AHUs 35AS and 35BS scored identically. The surveyors could see no difference between the two setups. Both were located at the bottom of a double-stack installation, displayed very mild risk issues because they were installed in parallel rather than perpendicular to the perimeter wall of the facility (with easily approachable access doors) and no obstruction from LTHW pipes or other duct/piping.

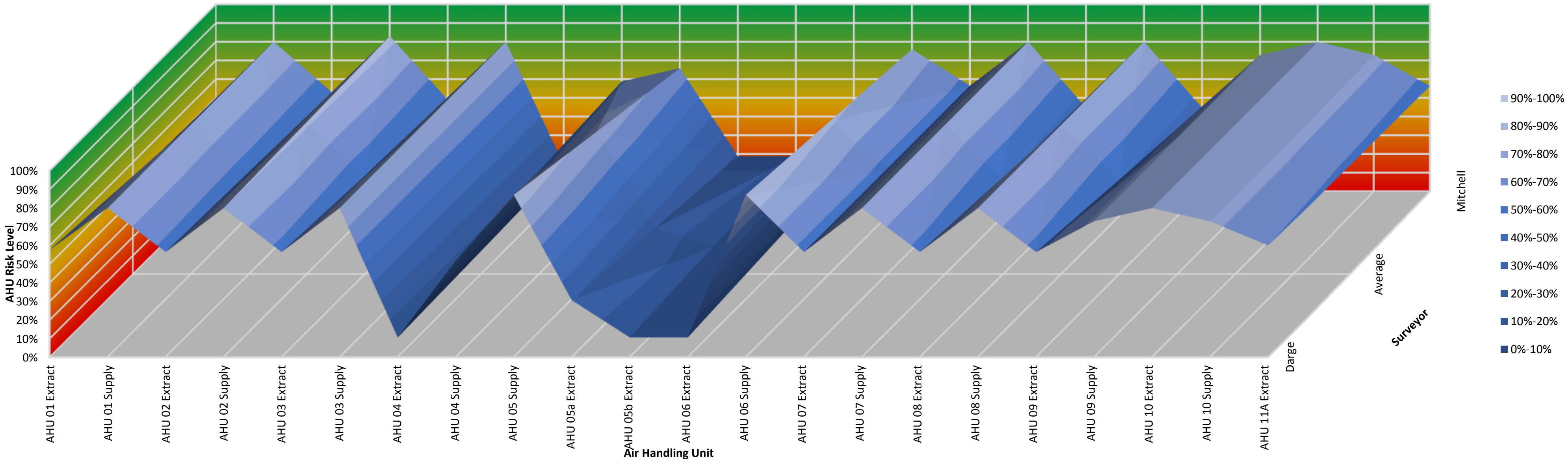


Figure 54: Engineering Risk Survey Results Graphs 1 to 5 (AHU1 to AHU DE05)

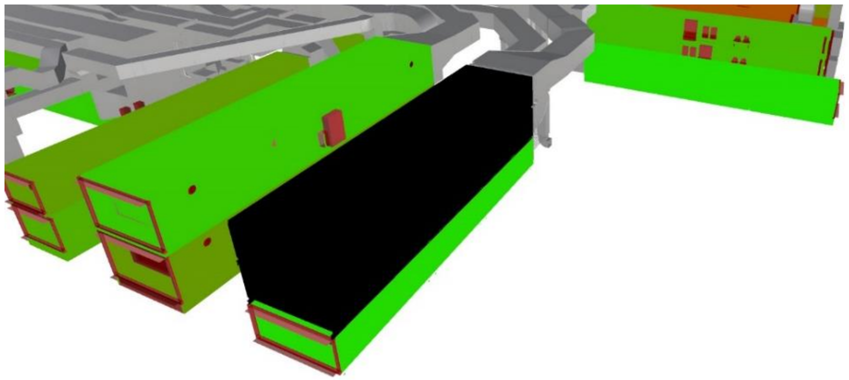


Figure 55: AHU37AS and 37BS -two empty air-handling units posing no lifecycle risk (black)

6.2.5 Air-Handling Unit 40E to Air-Handling Unit DE05

Graph 5 (in Appendix 13) displayed a local maximum of 80% (AHU 42AS, 42BS and 46S) and a minimum of 17% (AHU 42E). AHU 42AS, 42BS and 46S were all located off an internal thoroughfare within the building, which might explain the condition of equipment. The assets were not subject to the inevitable bumps and knocks caused by routine maintenance in the way that many other AHUs are, hence the low-risk level. AHU 42E was perhaps the most uniquely placed AHU in the facility. Located at the top of the only externally mounted triple-stacked unit on the 7th floor roof space, it demonstrated a high-maintenance level due to its open accessibility. The outdoor environment was also deemed to be severe because it meant exposure to degradation for any unit positioned in that way and being mounted on top of two other AHUs increased 42E's level of risk.

6.2.6 Other Survey findings

As can be seen from the results, only 110 of the 113 AHUs have been modelled. Perhaps the greatest discovery in the survey in terms of its overall impact on the lifecycle model funding profile concerns AHUs 33S, 37AS and 37BS. All three AHUs were found with either services unconnected, no internal components or no ductwork connected whatsoever. These assets will therefore appear black in the risk-level visualisation because they pose no risk. The upshot of this finding could yield upwards of £100,000 in lifecycle savings because of the units' inclusion for replacement in the current lifecycle model for AHUs at HCP1. Another by-product of the risk survey was the identification of defects by the surveyors, noted in the additional notes section of the proforma. The defects identified included:

- AHU 12E - one set of drive belts failed.
- AHU 15BS - steam leak on impulse line.
- AHU 24AE - slack drive belts.
- AHU 29BE - pulsing felt from drive.
- AHU DE01 - bulkhead light broken at rear.

The survey was conducted over a two-week period in July and August. It yielded results which demonstrated that not all AHUs are the same and that some tend to perform better in terms of life expectancy than others. This is predominantly due to specific factor categories. These categories were found to influence the risk levels of the AHUs and provide a good basis for profiling the replacement of their component parts. The surveyors did note that assigning years of failure to individual categories did lengthen the survey process more than they would have liked and that assigning equal weighting to each of the categories would be a more time-efficient method of surveying. However, the results yielded from this may be dubious because it was found that some categories were seen as more critical than others. The descriptions of the factor categories could have been made more surveyor-friendly.

The category descriptions were taken pseudo-verbatim from the ISO standard to ensure consistency. However, looking at the survey and the time spent with the surveyors, employing different terminology might help new users of the pro-forma better understand exactly what is implied by the description for each factor category. The surveyors also thought the BCIS range of 17 years was a time-consuming exercise because of the mathematics involved in assigning the year impact to factor categories.The number 17 was chosen because it provided upper and lower limits to the results based on current industry leading guidance. In future, it may be better to set the ratio to 10 and map the values accordingly. The survey was conducted using a tablet (rather than by hand) and, while the first batch of AHUs took longer than expected to assess (around 14-16 minutes), this made the overall speed of the survey faster, with some AHUs being completed in a matter of minutes due to the same factor categories applying to the same types of AHUs.

6.3 Paymech Risk-Level Results

The graph in Appendix 14 has been created by assessing the various functional areas, units and failure-event categories. As with the risk-based survey, the results are shown graphically to indicate that 0 (red) is high risk and green (1) is low risk. The actual financial implications deduced from the paymech calculations have been safeguarded and normalised for both data-privacy reasons and model data-import reasons respectively. The lowest deduction was just over £1,000 according to the paymech calculation (the FM offices) and the highest deduction was around £400,000. The findings are based on the fixed variables of the three available periods per day, with one 8-hour period affected during the day which saw one category C service failure (Importance level: Major).AHUs serving the cardiac theatre suites were found to be the most financially risky assets amongst the entire AHU system. AHUs 14AE to 18E – all extract units – were very highly regarded in terms of their criticality for two reasons. Firstly, the cardiac theatre suites are a place where lives are at risk; any healthcare facility is inevitably judged on its ability to keep mortality rates as low as possible. Secondly, the operating theatres are places with a non-negotiable level of environmental control because of the use of sterile equipment and the exposure of patients' internal organs to the environment within the room. HEPA filters are used in assets serving such critical rooms.The AHUs seen to be serving the least critical part of the hospital are AHU 44E and 44S, both serving the FM offices. This is because the staff working in these offices are neither hospital staff nor patients.

6.4 Risk Variables and their Weighting

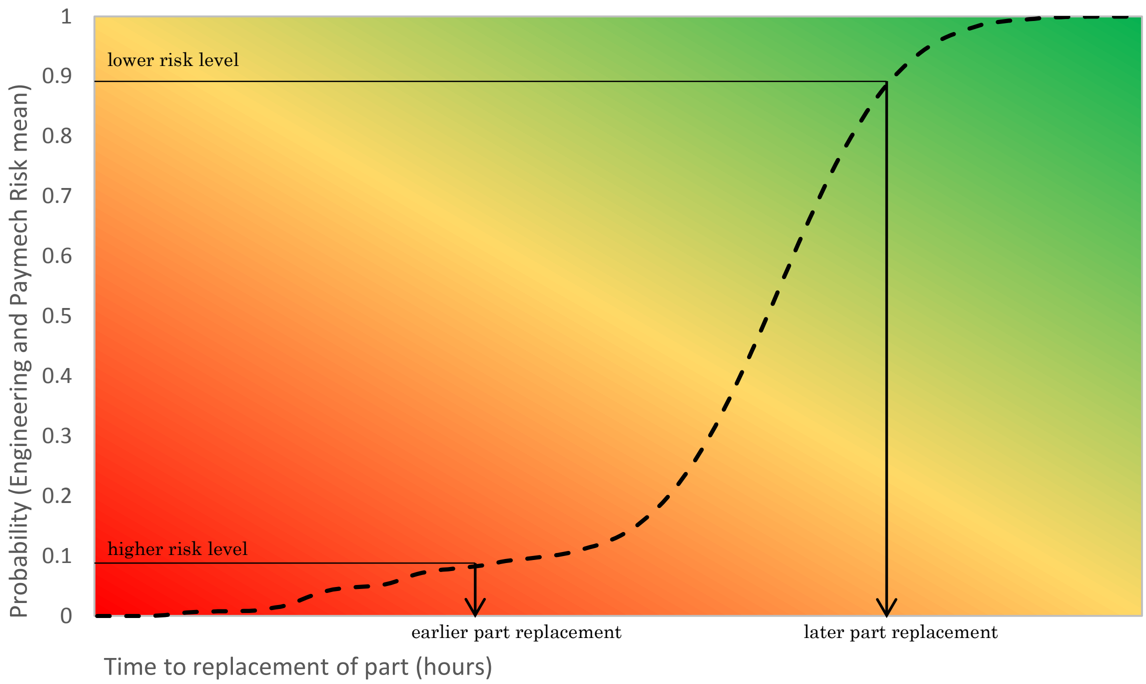


Figure 56: Time to replacement versus probability graph

Figure 56 above illustrates how the model differentiates between AHUs risk levels. The higher the risk (where 0 is the maximum risk level) the lower the expected lifecycle. This represents how the two types of risks feed into the lifecycle models replacement predictions. At this point, it is important to state that the suggested replacement will differ depending on the part's unique probability distribution. The risk level of the asset (i.e. the AHU) produces a risk value which is cross-checked against the distribution on a part-by-part basis.

6.5 CIBSE Simulated Distributions

The Monte Carlo simulation was based on the mean runtime as recommended by CIBSE. However, the constraints of each distribution needed to be defined to ensure that the results presented a fair representation of the distributed lifetimes per part given by CIBSE. The lower constraints of the CDFs were formed by truncating the minimum value to that suggested by the data collected from the portfolio. This added a further element of realism to the simulated results. The upper constraints were formed by removing all data between the 95% percentile range and upwards. Similar data collection and reduction exercises have been conducted previously (Kirkham & Boussabaine, 2005). Table 22 shows the CIBSE-recommended lifetimes (in years) for all parts within the AHUs. The mean runtime data collected from HCP1 (22.9 hours) was used and converted to give an estimated-hourly lifetime, to be used as input for the simulation. The selection of a suitable probability distribution is very important as it can have a significant effect on the results of the model (Kirkham, 2002). In the interests of model flexibility for decision-making purposes, the Weibull, Triangular and Rayleigh distributions have all been modelled. While the data collected across HCP sites has already been established as fitting well within the normal distribution parameters, the evaluation allows for a choice of distribution in lifecycle model to be made, beyond the 'recommended' profiles (Option 1) and provides the basis for the simulated conservative (Option 2), balanced (Option 3) and optimistic (Option 4) approaches. One hundred iterations were used in the simulation process and the results are presented below in Table 22. Because of the similarities in the lifespans and the combination of data for one or more parts in the HCP data, the cooling and frost coils, run-around and heating coils, extractor/supply fans and filters have been merged into one profile each. With regard to the filter profiles (because no empirical data was collected for this part and with filters recommended to have a 1-year lifetime, by CIBSE) a default value of zero was used for the local minima. While the majority of filters are assumed to fall under the maintenance umbrella and would therefore be excluded from lifecycle, in the case of bespoke filters (such as HEPA filters used in the AHUs serving the operating theatres) the cumulative-density functions were still useful because the cost of these parts would (in some instances) fall above the maintenance cap and therefore need to be included in the lifecycle. Zero silencer (attenuator) failures were recorded. This is most likely because the silencer is not a moving part and has an expected lifetime of 25 years, according to CIBSE. So rather than assuming a truncated start-life of zero, one standard deviation according to a normal distribution (based on the CIBSE life expectancy) is used.

Table 22: CIBSE recommended lifetimes and conversion to hourly data

				CIBSE LIFE						
	Recommended Life (Years)	Asset Install Date	Replacement Date	**Age when replaced**	**Years**	**Months**	**Days**	**Failure Date (Days)**	AHU runtime per day (hours)	**CIBSE Life**
Cooling Coil	15	01/01/2000	01/01/2015	15 Years, 0 Months, 0 Days	15	0	0	5475	22.90	125378
Frost Coil	15	01/01/2000	01/01/2015	15 Years, 0 Months, 0 Days	15	0	0	5475	22.90	125378
Heating Coil	15	01/01/2000	01/01/2015	15 Years, 0 Months, 0 Days	15	0	0	5475	22.90	125378
Run around Coil	15	01/01/2000	01/01/2015	15 Years, 0 Months, 0 Days	15	0	0	5475	22.90	125378
Control Panel	15	01/01/2000	01/01/2015	15 Years, 0 Months, 0 Days	15	0	0	5475	22.90	125378
Fan Supply/ Extract	15	01/01/2000	01/01/2015	15 Years, 0 Months, 0 Days	15	0	0	5475	22.90	125378
Flatbank Filter	1	01/01/2000	01/01/2001	1 Years, 0 Months, 0 Days	1	0	0	365	22.90	8359
Other filter	1	01/01/2000	01/01/2001	1 Years, 0 Months, 0 Days	1	0	0	365	22.90	8359
Polyseal filter	1	01/01/2000	01/01/2001	1 Years, 0 Months, 0 Days	1	0	0	365	22.90	8359
Humidifier	10	01/01/2000	01/01/2010	10 Years, 0 Months, 0 Days	10	0	0	3650	22.90	83585
Invertor	20	01/01/2000	01/01/2020	20 Years, 0 Months, 0 Days	20	0	0	7300	22.90	167170
Motor	15	01/01/2000	01/01/2015	15 Years, 0 Months, 0 Days	15	0	0	5475	22.90	125378
Shut-off damper	15	01/01/2000	01/01/2015	15 Years, 0 Months, 0 Days	15	0	0	5475	22.90	125378
Silencer	25	01/01/2000	01/01/2025	25 Years, 0 Months, 0 Days	25	0	0	9125	22.90	208963

A statistical distribution-generated set can be seen in Figure 57, below (Cooling and frost coil). The remaining parts distributions from Table 22 and their full statistics can be found in Appendix 15.

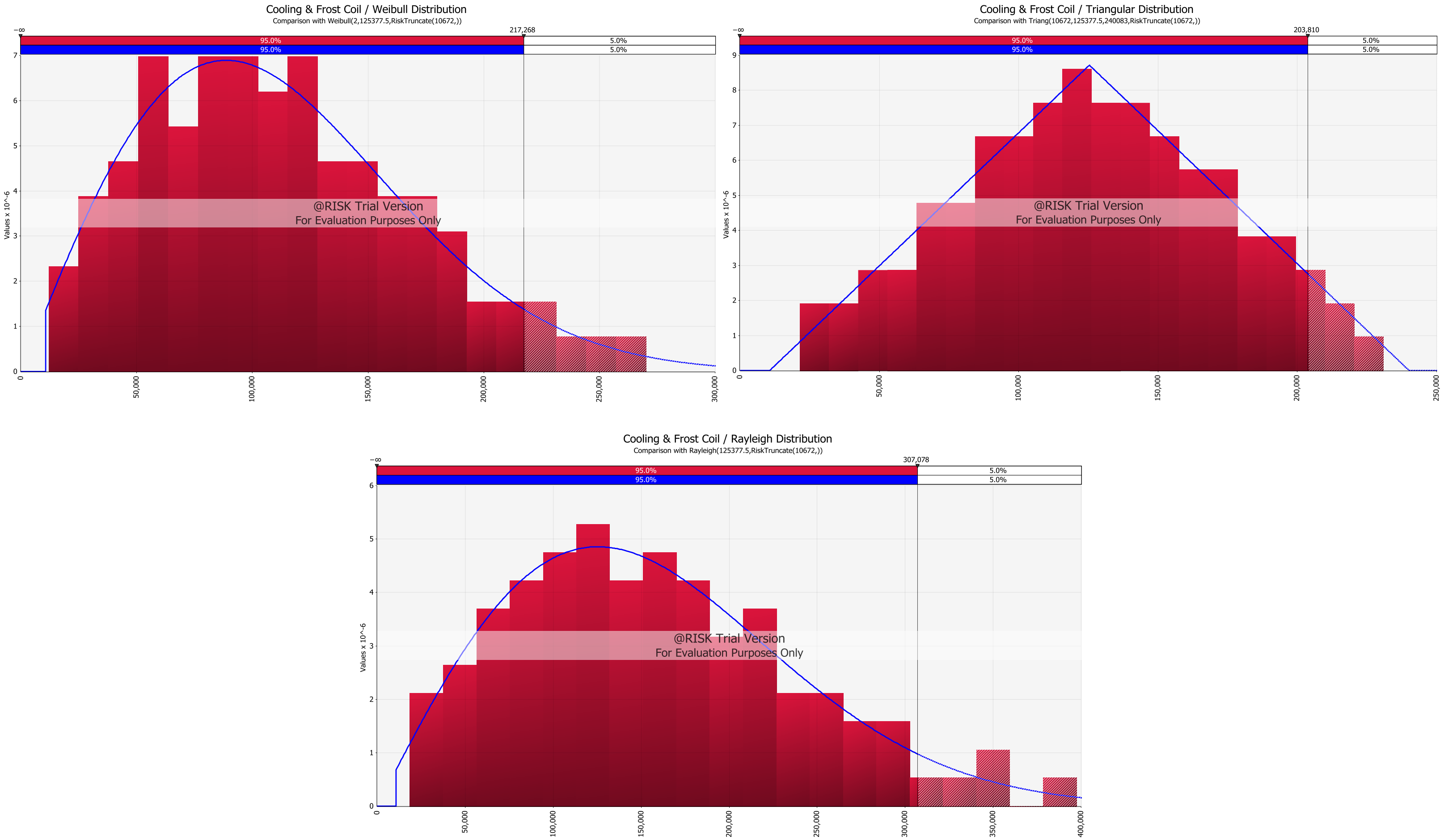


Figure 57: Cooling and frost coil failure distributions

Distribution	Lifecycle Pseudonym	Risk Profile	Parameters						Min	Max (95% perc.)	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			y	α	β	Min life	Mean Life	Max Life							
Weibull	Conservative	Low	0	2	125,378	n/a	n/a	n/a	12489.5	210940	111707.2	57407.09	3.29+E09	0.5746993	2.953995
Triangular	Balanced	Medium	n/a	n/a	n/a	10,672	125,378	240,083	25518.3	202604.8	125432.2	47092.8	2.21+E09	0.01120863	2.429628
Rayleigh	Optimistic	High	n/a	n/a	125,378	n/a	n/a	n/a	13995.44	298652.1	157165.3	80874.23	6.54+E09	0.5408548	2.858517

6.5.1 Summary of Results

The nature of lifecycle prediction is based on the CIBSE data presented in Table 22. The simulation of three differing cumulative-density functions provides flexibility in assuming failure rates for the differing parts.

Table 23: Simulated lifetimes converted from hours to years

	Weibull Distribution		Triangular Distribution		Rayleigh Distribution	
Part	Minimum Life (yrs)	Maximum Life (yrs)	Minimum Life (yrs)	Maximum Life (yrs)	Minimum Life (yrs)	Maximum Life (yrs)
Cooling & frost coil	1.49	25.61	2.72	24.05	2.35	36.17
Heating & Run around coil	2.60	25.96	4.26	23.38	3.35	36.56
Control Panel	10.03	18.62	10.61	18.40	10.08	37.29
Fan	2.82	25.65	3.14	23.49	2.80	35.95
Filter	0.09	1.72	0.12	1.68	0.08	2.41
Humidifier	8.63	19.03	8.76	10.95	8.66	25.82
Inverter	5.58	34.95	7.45	29.70	5.83	49.10
Motor	2.41	13.11	2.96	10.88	2.49	18.06
Shut-off damper	6.58	26.66	7.54	20.67	6.52	36.35
Silencer	5.29	43.49	5.79	38.52	5.72	60.14

One of the key drawbacks in trying to deduce and simulate profiles for each of the parts is the distinct lack of data in the field of lifecycle. Because of its commercial value, few manufacturers or companies are prepared to divulge hard data (hence the data collection) and so the majority of the Lifecycle Costing industry is dependent on the 'single point estimate' given by CIBSE. The table above illustrates the output of the Monte Carlo simulations. The results have been converted into yearly lifetimes for import into the lifecycle model. By and large, the Weibull distribution demonstrates the most modest lifecycle replacement prediction and the Rayleigh distribution provides a riskier standpoint. The maximum life of any component under any of the simulations is 60.14 years. This silencer replacement, according to the Rayleigh (simulated optimistic) simulation, is perhaps somewhat optimistic. However, given the nature of the part and its purpose (sound proofing), it is unlikely to require routine maintenance in the same way that some of the rotating assets do and, as zero failures for this part have been recorded to date, the assumption may stand until at least one of these parts has been recorded as being replaced.

6.5.1.1 Option 2: The Conservative Approach

One of the key drawbacks was the fact that the beta value for the Weibull distribution could often be the same because of the similarities of lifetime expectancies across different parts, as dictated by CIBSE. The differing minima, as dictated by the first recorded HCP failure, helped to ensure that the part differences were picked up. The alpha value remained at 2 for the majority of failure distributions. However, the control-panel failure distribution's alpha value was altered to 5, to take the comparatively high minimum value (83,790 hours) into account. This ensured that the Weibull curve-shape was consistent in that its indications of peak failure in time occurred around 30% into the distribution. The two parts which demonstrated the latest initial replacement also demonstrated the narrowest variation in terms of part cost.

6.5.1.2 Option 3: The Balanced Approach

The balanced approach (Triangular distribution) received 3 input variables, the minima, mean and maxima values. The minimum value was the earliest failure recorded from the HCP data set, and this meant that there was no truncation of values necessary as with the Weibull and Rayleigh distributions. The mean value was taken to be mean lifetime from CIBSE and the maximum was taken to be the mean minus the minimum to ensure consistency. The results of the balanced approach are fairly consistent. The one-part failure curve which could be deemed to be rather more conservative is that of the control panel, because the control panel displayed an unusually high first failure rate according to the HCP data. As to be expected, the skewness of the results from the balanced approach were both positive and negative. Ranging from -0.044 (silencer) to +0.021 (filter). The Triangular distribution is consistent in terms of its asymmetrical structure and the marginal skewness figures represent this. The truncated minimum values for each part are responsible for the slight change seen in skewness across the parts. Kurtosis across the parts under the triangular profile are high, often >3. The reason for this figure is the fact that the distribution is triangular in shape and therefore there is almost zero flatness at the peak of the histogram profile.

6.5.1.3 Option 4: The Optimistic Approach

One of the key drawbacks was the fact that the Rayleigh distribution had only one variable - alpha. This meant that where CIBSE recommended that different parts have the same or similar lifespans, there would be little difference between them. However, the inclusion of real data as a means of truncation for the local minima ensured that there would be differences between different parts with regard to the optimistic approach. The Rayleigh distribution produced largely positive skewness results, ranging from 0.55 (filter) to 0.96 (humidifier). This suggests that the distribution is marginally positively skewed and suggests a slightly front-loaded view of failures over time, for all parts.

6.6 HCP Hybrid Distributions

The HCP hybrid cumulative-density functions were created using a combination of real data collected from the HCP hospital data-collection exercise and was (where necessary) combined with the CIBSE data. The output of using both real and CIBSE data is a *recommended* profile (option 1) for each of the parts respectively. The HCP-hybrid CDFs provide a fourth profiling option for the lifecycle model. It was necessary to combine the real data with the guidance data because none of the parts for which data was collected exhibited a 100% failure rate. This meant that only a portion of the curve could be represented using the real data. Prior to creating the profiles, a probability-plotting exercise and Anderson-Darling test was performed on the data to test its fit to a normal distribution curve.

As discussed prior, no data was collected for the following parts:

- Filters
- Silencers

The reason is that they are often not recorded under lifecycle (in the case of filters) or that they are recorded under lifecycle but have not exhibited any failures (in the case of silencers). In any case, where zero replacement data has been collected, the balanced (Triangular) profile for a part will be used in its place.

6.6.1 Data Fitting: Probability Plotting and Anderson-Darling Testing

The data-collection exercise did not record 100%-part failure for any subcomponent, and so for that purpose, it was difficult to determine the hypothetical shape of the curve, had all the replacement-data samples been collected. The following histogram illustrates such a point.

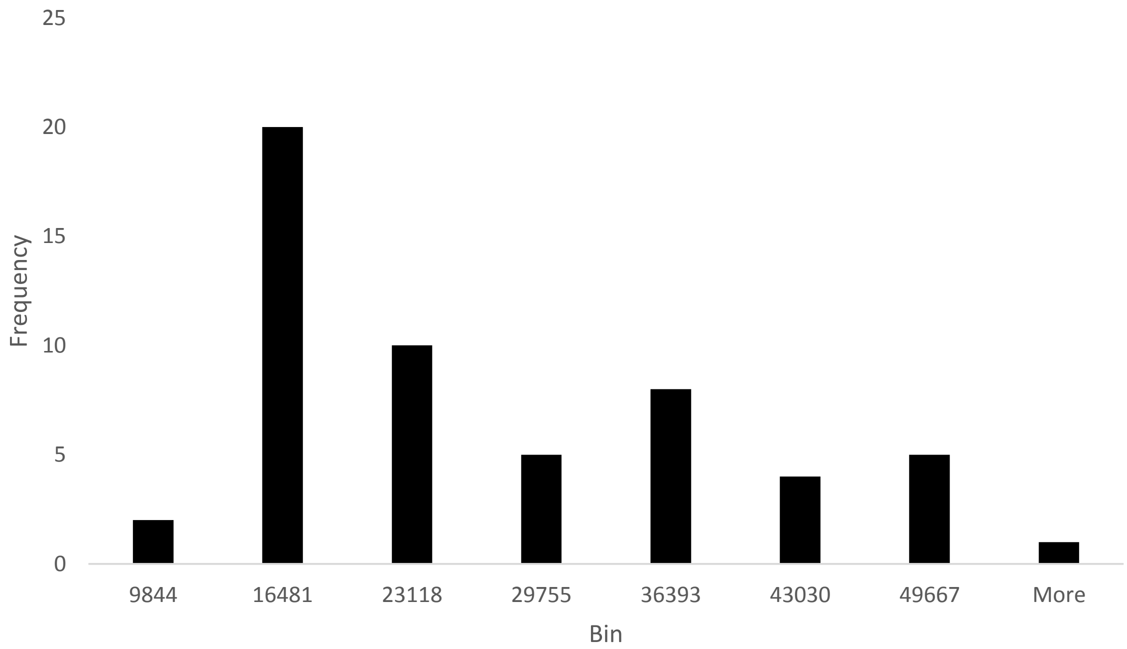


Figure 58: Motor histogram

It can be argued that the use of histograms (where data is limited or incomplete) provides limited information on the shape of the curve. Before modelling the profiles of the parts based on the data collection, a probability-plotting exercise combined with an Anderson-Darling test was undertaken on each of the parts' data samples in order to analyse the goodness of fit. A normal probability plot was used as the null hypothesis. A normal probability plot can be used to determine if small sets of data come from a normal distribution without necessarily having the whole data set (Kirkham, 2002). The normal probability-plotting exercise allowed for data analysis for calculating which failure distribution would be best for extrapolating the values of the remaining part of the curve (which had not been collected because the parts had yet to fail).

Figure 59 (below) illustrates the probability plot based on the cooling and frost-coil data sample. The remaining parts' probability plots can be found in Appendix 16. As can be seen from the probability plots, each of the parts (save the filters and silencers, due to an absence of data) exhibited a fair to good fit under regression, illustrating a minimum value of 0.8951 (motors) and a maximum value of 0.9623 (cooling and frost coil). The reason for the poorer fit ratio amongst motors and inverters may be due to the fact that the invoice data collected for each of the parts discloses the purchase date of the part – not the replacement date. The multiple data points at any given time – as can be seen at around 47,000 hours in the inverter-probability plot – could be the result of a bulk purchase of parts (perhaps for reasons of economies of scale) with staggered replacements thereafter. While numerous works allude to a three-part Weibull distribution as underpinning the Bathtub curve (and indeed this has been used in the creation of the CIBSE-based curves, the staple diagram for any failure prediction) the data collected by-and-large tends towards a normal distribution. As discussed during the literature review, the AD test will ensure that the hybrid-replacement curves adhere to a normal distribution or not. The AD test was used here in preference to the other compatibility-of-fit tests discussed in the literature (Maio, 2000; Kirkham, 2002) because of its ability to detect any discrepancies in the tails of the distributions.

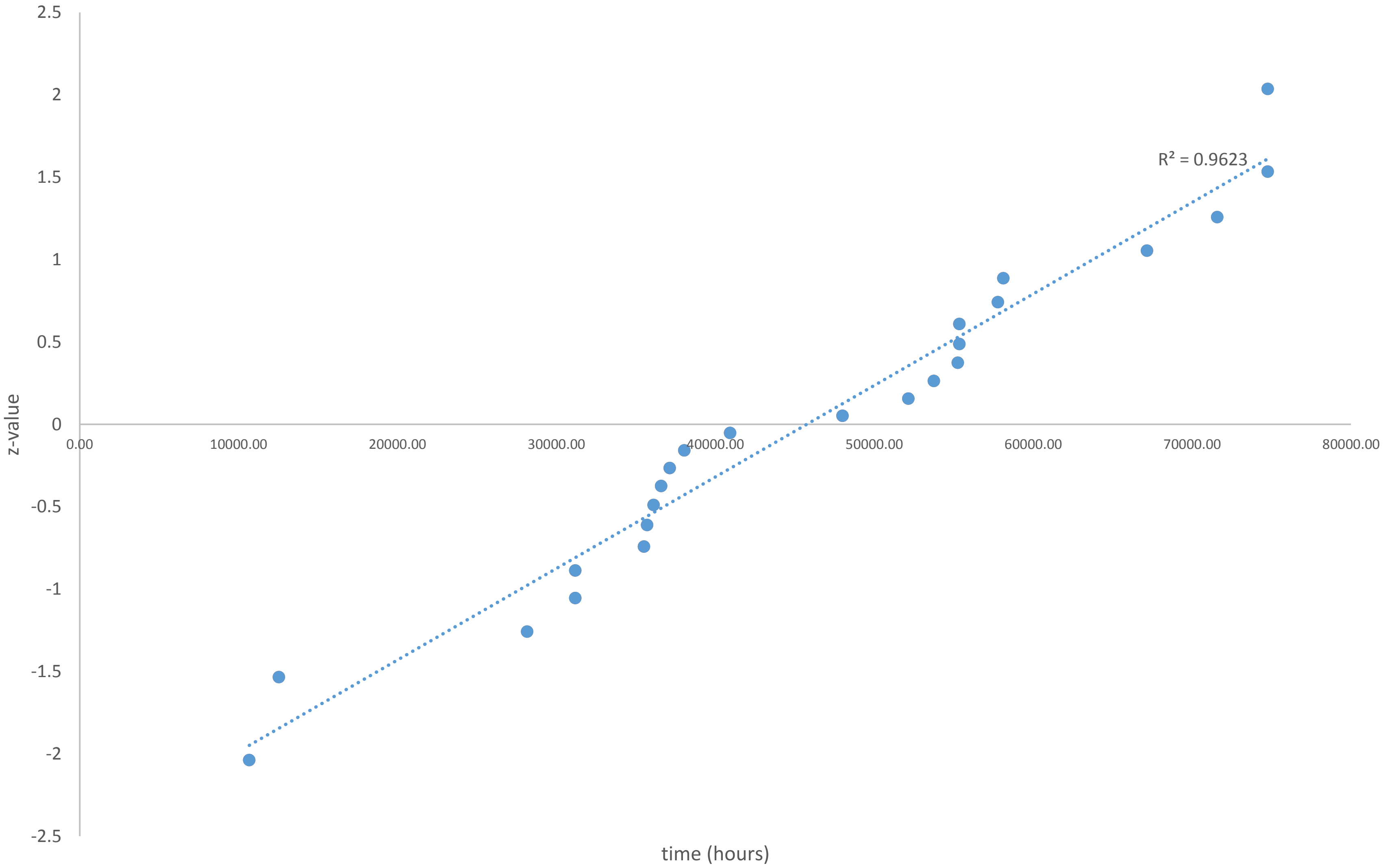


Figure 59: AHU component part probability plot based on data collected from HCP hospitals (cooling and frost coil data points)

The Anderson-Darling test of the sample data highlighted the following statistics:

Table 24: Results from the Anderson Darling Test and Regression analysis

Part	Cooling/frost coil	Heating/run around coil	Control panel	Fan	Humidifier	Inverter	Motor	Shut-off damper
Sample	24	20	4	22	5	48	55	4
P-Value	0.333	0.386	0.600	0.2531	0.245	0.00044	3.35E-05	0.339
Regression Analysis	0.9623	0.9563	0.9522	0.946	0.9131	0.8996	0.8951	0.8983
Accept null hypothesis?	Y	Y	Y	Y	Y	N	N	Y

All p-values apart from the inverter and motor (R^2 = 0.00044 and 3.35E-05 respectively) sample data returned a value of $p>0.05$. Therefore, the null hypothesis that the data is normally distributed can be accepted for all the data sets, apart from those associated with the inverter and motor. The reason for the rejection of the null hypothesis in these two instances is because there is a front loading of data points. Where the null hypothesis was rejected, the data will be used to produce a hybrid curve based on the Weibull distribution because it is a front-loaded failure curve and therefore best representative of the front loaded nature of the data collected. Apart from these two parts, the HCP-hybrid curves were formed in conjunction with a normal distribution based on the probability plots and AD testing.

The lower limit of the distribution is set by using the *latest* recorded failure so that the profiles consist of HCP data for the first part of the curve and Monte Carlo data for the remainder. Rather than using the first recorded data point for each part, by using the last data point, it meant that the profile would be a truer extrapolation from the data collected to date.

$$I_{mc} = \left(\frac{n}{PR} \, .100\right) - n$$

- where *I* is the number of *iterations* necessary for the part, *n* is the number of *recorded failures* and *PR* is the part ratio based on HCP1 air-handling unit observations.

The upper bound was left open ended in this case because all the data points in the simulation were needed to achieve the ‘probable number of parts’ figure.

Table 25: A table showing the mixture of HCP and CIBSE data points

Part	Cooling/frost coil	Heating/run around coil	Control panel	Fan	Humidifier	Inverter	Motor	Shut-off damper
Sample	24	20	4	22	5	48	55	4
Earliest Failure	10,672	21,720	83,790	21,091	71,694	45,414	9,844	53,625

Latest recorded failure	74,750	96,439	92,394	83,566	99120	104,736	56,304	67,106
HCPs with recorded failures	WHI/ JCU/QEH /OJR	QEH/ JCU/ WHI	WAL	QEH/ WHI/ JCU/ OJR	HRM/ JCU	QEH/OJR/WH I/WAL/HRM	QEH/WHI/HR M/WAL/JCU	JCU
Probable number of parts based on part ratios	236	404	51	339	42	333	418	130
% Failed to date	9%	4%	8%	6%	12%	14%	13%	3%
Simulated data points	212	384	47	317	37	285	363	126
Hybrid Distribution	Normal	Normal	Normal	Normal	Normal	Weibull	Weibull	Normal

In terms of variables for the distribution simulation, the two variables to derive were the mean (μ) and the standard deviation (σ). The mean was taken to be the one set by CIBSE and the standard deviation was taken to be the variance of the mean of the values for the data points within the HCP sample.

6.6.2 Cooling and Frost Coil Distribution

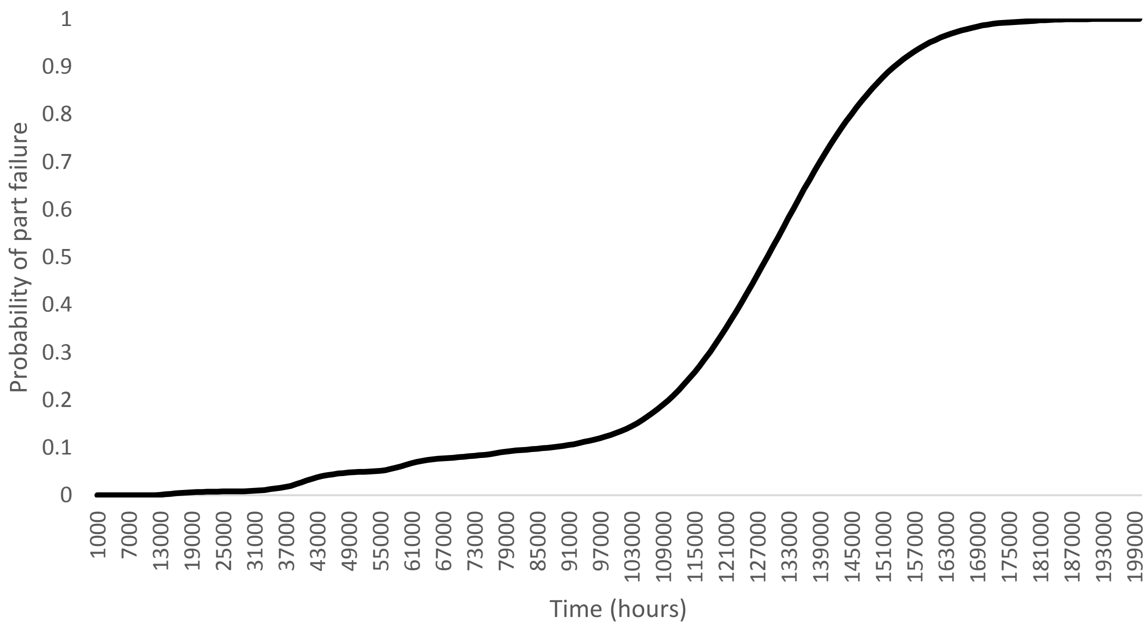


Figure 60: Cooling and Frost Coil Hybrid distribution

Table 26: Cooling and frost coil statistics

Distribution	Lifecycle Pseudonym	Risk Profile	Parameters		Min	Max	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			μ	σ							
HCP / Normal	Recommended	Medium	125,378	17,197	10,672	176,907	117,380	29,519	8.71E+08	-1.4314	2.308947

The moving average of the original data was taken over three time steps and the damping factor under exponential smoothing was set at 0.8. The mean was taken to be the one set by CIBSE and the standard deviation was taken to be the variance of the mean of the values for the data points within the HCP sample. As can be seen from Figure 59, the data, as predicted under the Anderson-Darling test, conforms well to the normal distribution. The lower bound was 10,672 (1.27 years) as set by the first recorded piece of HCP data. The lower bound of the CIBSE simulation was 9,654 with a bounded minimum of 10,672. The Monte Carlo simulated 212 remaining part failures returned a maximum value of 176,907 hours (21.2 years). This is because the simulation was left *unbounded*. The mean for the hybrid data set was found to be 117,380 (14 years). The hybrid data set was found to have a skewness of -1.4314, indicating a slight back loading of data. However, this is in part due to the fact that the HCP data occupies the left tail of the histogram and has been set as fixed quantities, thus meaning the left tail is fixed entity. The kurtosis of the data set was found to be 2.308947 and further establishes the fact that the almost asymmetrical distribution has a tail to the left. The variance was found to be 8.71^{08}.

6.6.3 Heating and Run-Around Coil Distribution

The heating and run-around coil simulation consisted of 384 simulated data points. The moving average of the original data was taken over three time steps and the damping factor under exponential smoothing was set at 0.8. As mentioned previously, the mean was taken to be the one set by CIBSE and the standard deviation was taken to be the variance of the mean of the values for the data points within the HCP sample. The data fits well to the normal distribution and is reflected in the high regression-analysis statistic derived from the probability plot (r^2>0.95). The lower bound of the data set was 21,270 as applied by the first recorded data set (2.6 years). The maximum value predicted was 191,286 hours (22.9 years). The mean for the hybrid data set was 126,313 (15.1 years), less than 1,000 hours different to the CIBSE guidance indicating a good fit between the HCP data and the normal distribution.

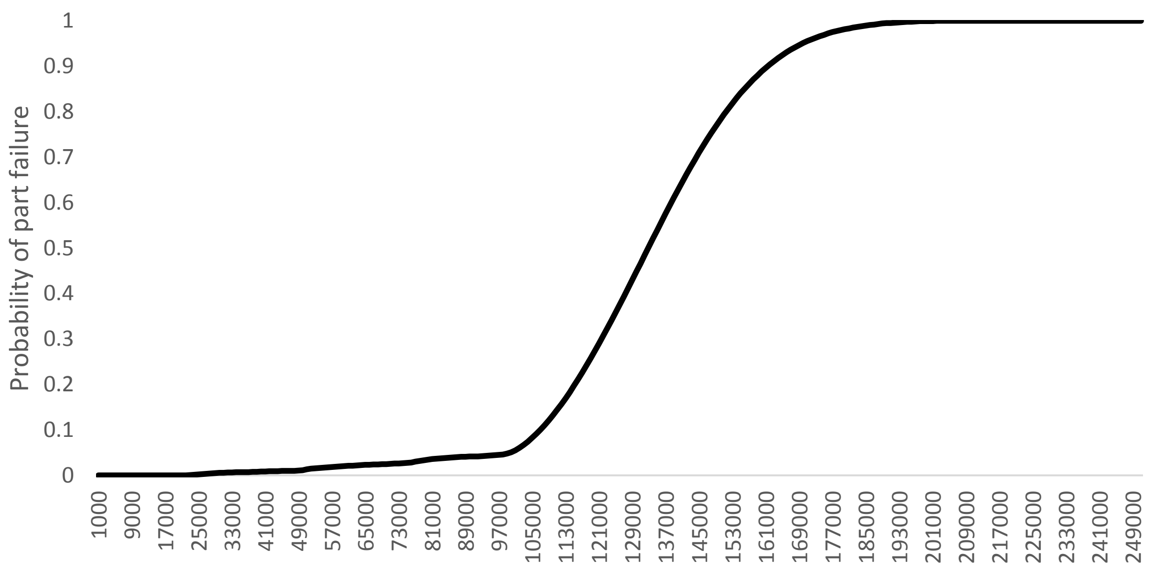


Figure 61: Heating and run around coil hybrid distribution

Table 27: Heating and run around coil statistics

Distribution	Lifecycle Pseudonym	Risk Profile	Parameters		Min	Max	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			μ	σ							
HCP / Normal	Recommended	Medium	125,378	22,528	2,1720	191,286	126,313	24,329	5.91E+08	-0.87843	2.874905

The hybrid data set demonstrated a skewness of -0.87843, indicating a slight back loading of data and conforming to the slightly higher mean life expectancy for the part. The kurtosis of the data set was 2.874. This indicates that there is a wider spread of data points in the left tail of the curve and suggests that the slope of the curve predicted by the simulation could be slightly flatter if all the data on the coils was available. The variance was 5.9108.

6.6.4 Control Panel Distribution

The control panel consisted of 47 simulated data points totalling 51 when combined with the 4-point data sample collected from the hospitals. The moving average of the data was smoothed over three time steps and the damping factor under exponential smoothing was set at 0.8. The data fits well to the normal distribution based on the p-value of 0.600 and r2 value of >0.95. The lower bound of the data set was 83,790 hours, according to the first recorded data point. This translates to a yearly minimum of just over 10 years. The maximum value predicted was 209,278 hours (25 years). The mean for the hybrid data set was found to be 133,670 (16 years).

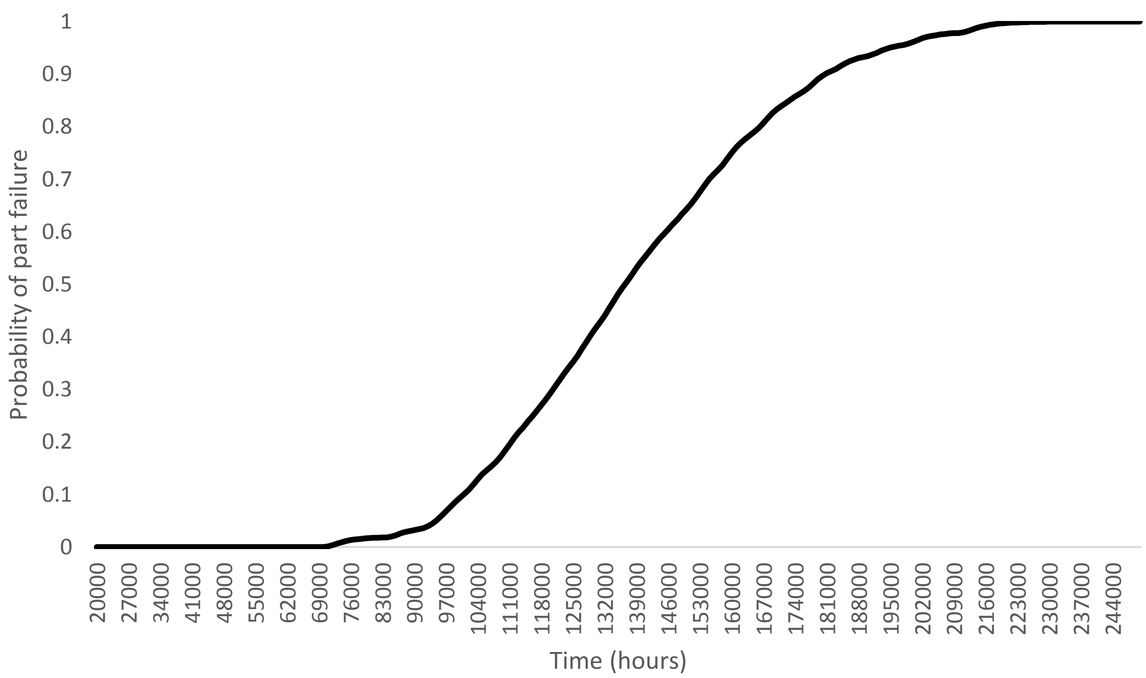


Figure 62: Control panel hybrid distribution

Table 28: Control panel statistics

Distribution	Lifecycle Pseudonym	Risk Profile	Parameters		Min	Max	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			μ	σ							
HCP / Normal	Recommended	Medium	125,378	36,768	83,790	209,278	133,670	29,854	8.91E+08	0.437237	-0.35397

The hybrid data set was found to have a skewness of 0.437, indicating a slight front loading of data. The kurtosis of the data set was found to be -0.354. This indicates that there is a marginally wider spread of data points in the right tail of the curve. However, because the kurtosis value is so slight there will be little to no difference between the tails of the curve when viewed on a cumulative density graph (shown in Appendix 17). The variance was found to be 8.9108.

6.6.5 Supply and Extract Fan Distribution

The supply and extract fans profile is comparatively sparse in comparison to profiles underpinned by CIBSE's 15-year life-expectancy figure. This is partly due to the comparatively high number of recorded failures (22) along with the low first replacement ratio at 21,091 hours (2.5 years) at HCP2 and the wide range covered between this and its last recorded failure at 83,566 hours. The skew of the data set is negative at a value of -1.07841, further highlighting the impact of the inclusion of the HCP data and moving the normal distribution away from its naturally occurring asymmetrical shape. The standard deviation of the hybrid curve has increased from 19,954 to 25,877. Again, this acts as an indication of the inclusion of the two data sets. The fans' typical s-curve displayed a minimum, maximum and mean value of 21,091, 180,543 and 121,636 hours respectively. Translated into years at the standard metric of 22.9 hours of runtime per day, these figures equate to 2.5, 21.6 and 14.6 years.

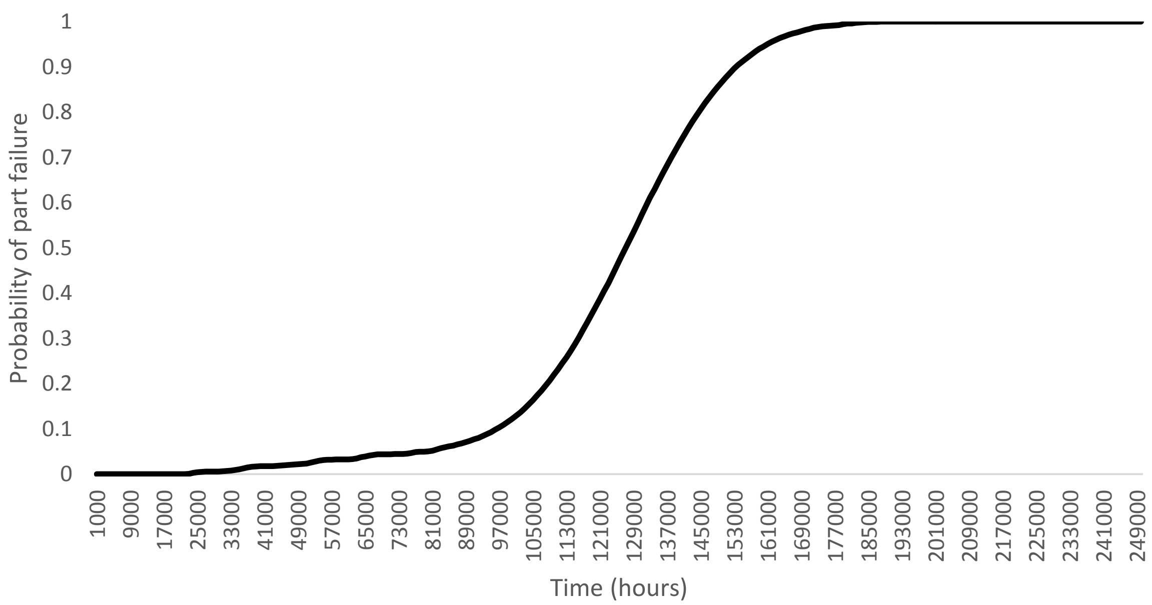


Figure 63: Fan (supply and extract) hybrid curve

Table 29: Fan (supply and extract) statistics

Distribution	Lifecycle Pseudonym	Risk Profile	Parameters		Min	Max	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			μ	σ							
HCP / Normal	Recommended	Medium	125,378	19,954	21,091	180,543	121,636	25,877	6.69+E08	-1.07841	2.411784

6.6.6 Humidifier Distribution

There were 5 sample data points for the humidifier data collection ranging from 71,964 to 99,120 hours.

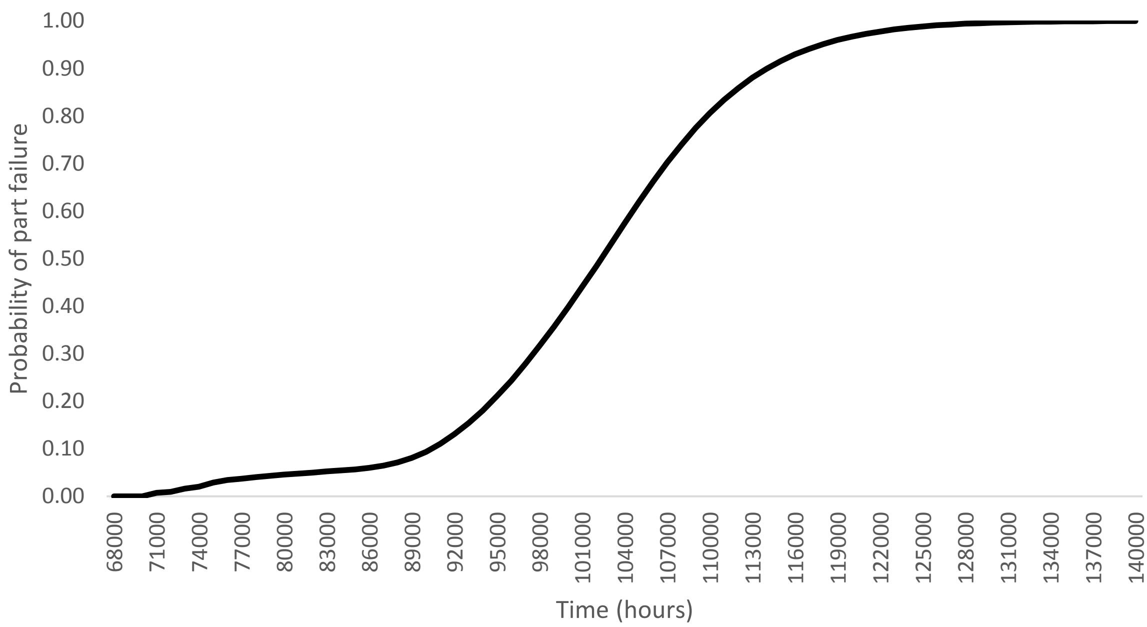


Figure 64: Humidifier hybrid curve

Table 30: Humidifier statistics

Distribution	Lifecycle Pseudonym	Risk Profile	Parameters		Min	Max	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			μ	σ							
HCP / Normal	Recommended	Medium	83,585	11,026	71,964	117,136	104,124	7828.936	6.12E+07	-1.89219	6.855024

The percentage replaced to date is 12% (5 of 42). It should be noted that the humidifier did display one of the lower r^2 coefficients from regression analysis, a little over 0.91. This raises further questions as to what the *limit* should be when deducing whether a data set conforms to a certain distribution or whether, in this instance, the null hypothesis should have been rejected and an alternative profile for extrapolation should have been used instead. The lower bound of the data set was 71,964 (8.6 years) as set by the first recorded data point. The Monte Carlo-simulated 37 remaining-part failures returned a maximum value of 117,136 hours (14 years). This is because the simulation was left unbounded.

However, the mean for the hybrid data set was found to be 104,124 (12.45 years). The distance between the mean and maxima further highlights the narrow range. The hybrid data set was found to have a skewness of -1.8, indicating a back loading of data. The kurtosis of the data set was found to be 6.855 and further establishes the fact that the almost asymmetrical distribution has a tail to the left.

6.6.7 Inverter Distribution

The inverter was modelled using a Weibull-simulated distribution because the results from the probability plot and Anderson-Darling test returned figures of r^2= 0.8996 and p=0.00044.

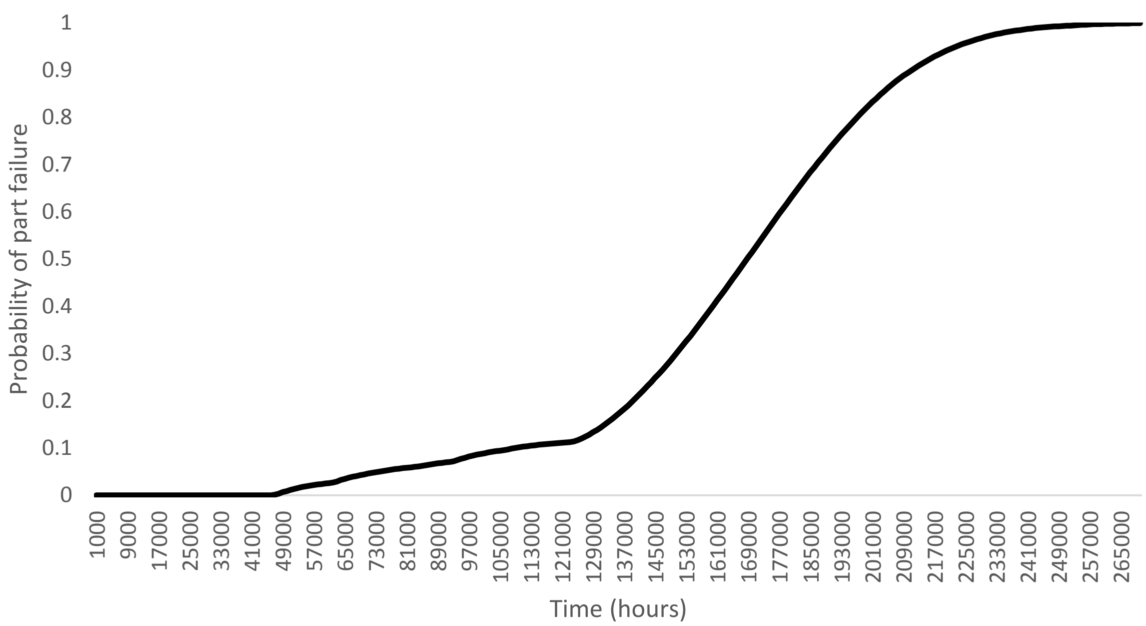


Figure 65: Inverter hybrid curve

Table 31: Inverter statistics

Distribution	Lifecycle Pseudonym	Risk Profile	Parameters		Min	Max	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			α	β							
HCP / Normal	Recommended	Medium	5	167,170	45,414	249,008	153,781	39,481	1.55+E09	-0.82349	0.868242

Alpha (scale) and beta (shape) values were 5 and 167,170 (mean) respectively. As mentioned in Chapter 3, there is no hard and fast rule for assigning an alpha value. However, the higher the value, the narrower the profile. Five was seen as an apt figure to use because it returned an unbounded upper limit of 249,008 hours (this equates to 29.8 years) which, for a part with a recommended CIBSE lifetime of 20 years, provides a reasonable spread of future failures. The scale parameter may be altered to avoid ‘kinks’ in the curve but with the HCP data and the number of parts in total being fixed variables, this could only have been avoided by elongating the distribution. Under these alpha and beta parameters, the minimum and mean values were found to be 45,414 and 153,781 hours (5.4 and 18.4

years) respectively. The profile displayed a slightly negative skew, which indicates a slightly back-loaded profile. The kurtosis value was found to be 0.868, with a standard deviation of 39,481. The Weibull distribution was used because the HCP data points did not conform to a normal distribution for this part. The Weibull was seen as the default distribution to model against for three reasons. Firstly, the data-sample points as observed from probability plotting were non-conformative to a normal distribution and displayed a low r2 value (0.8996). Secondly, the Anderson-Darling test returned a rejection of the null hypothesis. The Weibull curve is the failure distribution which forms the iconic Bathtub curve. Finally, the p-value falls below 0.005 and so according to the Anderson-Darling test, there should be a rejection that the data points form the beginning of a normal distribution curve.

6.6.8 Motor Distribution

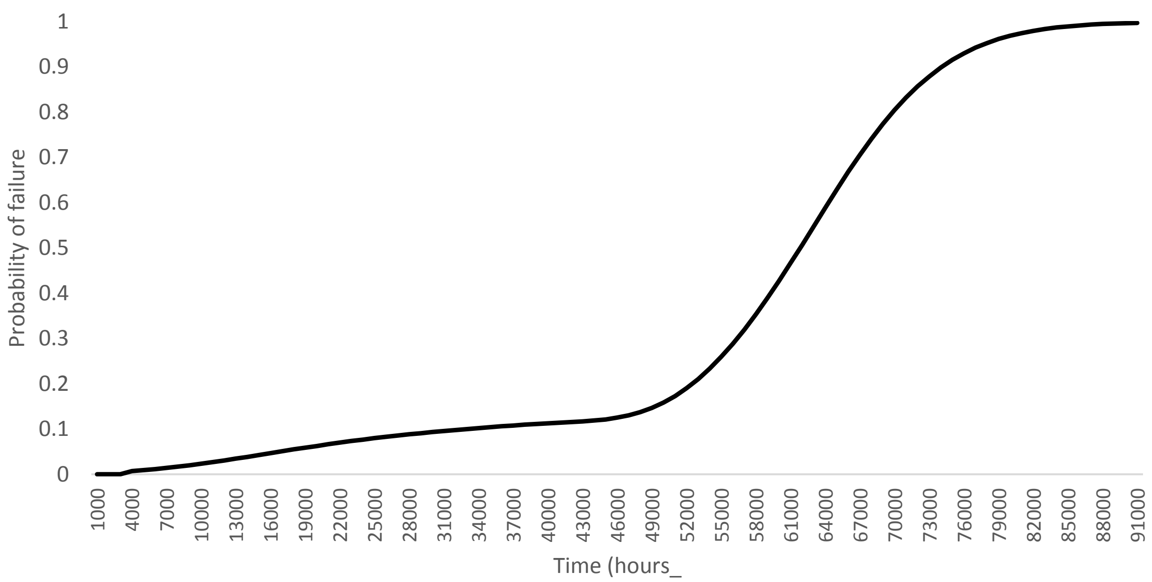


Figure 66: Motor hybrid curve (CIBSE &HCP)

Table 32: Motor Statistics

Distribution	Lifecycle Pseudonym	Risk Profile	Parameters		Min	Max	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			α	β							
HCP / Normal	Recommended	Medium	5	62,689	9,844	84,790	59,024	15,129	2.28+E08	-2.04985	3.472559

While these figures are statistically aligned to the other parts of the AHU, motors are unique in that they are often run in tandem with another motor and therefore the runtime of the AHU does not accurately represent the motor's runtime. Therefore, the runtimes of each component recorded failure (to date) will be assumed to be 50% of the time then divided by two to take account of the fact that although an AHU may be run for 24 hours, it is likely that the motor has only been used for half this time. This is a more risk-averse approach because the AHUs classed as serving critical areas always contain two externally mounted motors. The motor was modelled using a Weibull-simulated distribution because the results from the probability plot and Anderson-Darling test returned figures of r2= 0.8951 and p=0.000033. The profile displayed a highly negative skew, which indicates a back-loaded profile. The kurtosis value was found to be 3.472, with a standard deviation of 15,129. Alpha (scale) and beta (shape) values were 5 and 62,689 (mean) respectively. As mentioned in Chapter 3, there is no hard and fast rule for assigning an alpha value. However, the higher the value, the narrower the profile. Statistical guidance on the topic suggests 3.5, however in this instance 5 was seen as a realistic figure to use because it returned an unbounded upper limit of 84,790 hours (10.1 years). This equates to 20.3 years at the default runtime per day, divided by a factor of two. To use a lower scale factor would risk elongating the range and kurtosis of the data set and risk elongating the proposed lifetimes of what is seen to be perhaps the most crucial of the AHU parts because of the rotating subcomponents. Subcomponents such as bearings are a common feature in HFM teams' reactive maintenance regimes and therefore a risk-averse approach was seen as being the optimum assumption in this instance. Under these alpha and beta parameters, the minimum and mean values were found to be 9,844 and 59,024 hours (1.18 and 7.1 years) respectively.

6.6.9 Shut-off Damper Distribution

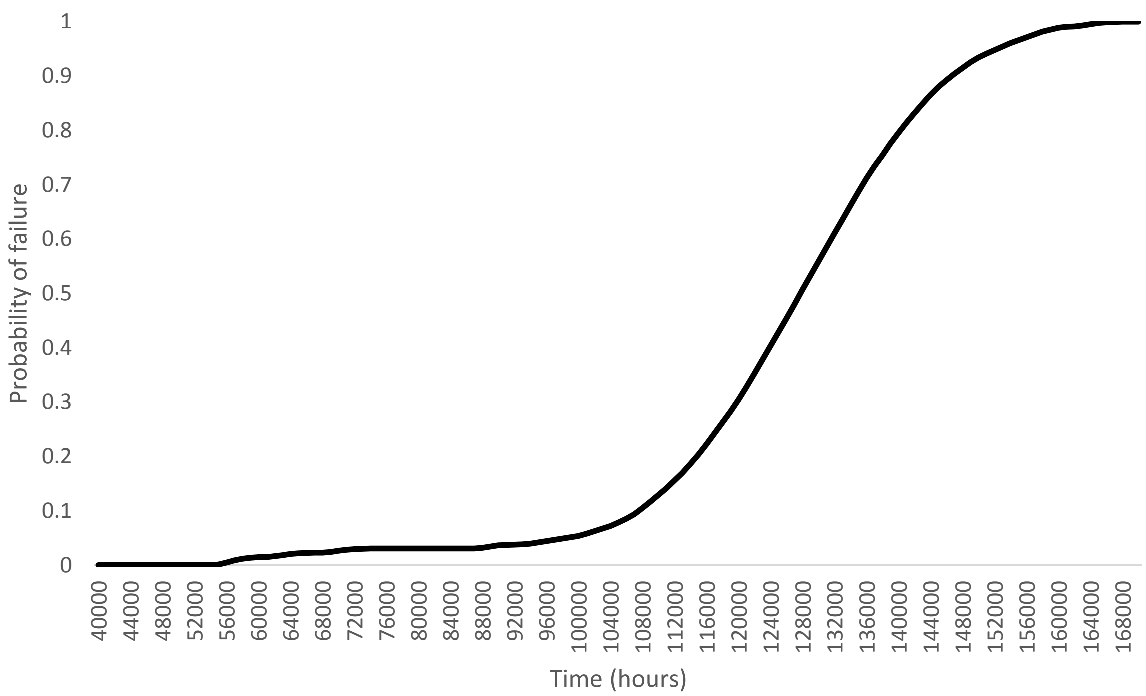


Figure 67: Shut-off damper hybrid curve

Table 33: Shut-off damper statistics

Distribution	Lifecycle Pseudonym	Risk Profile	Parameters		Min	Max	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			μ	σ							
HCP / Normal	Recommended	Medium	83,585	14,379	53625	161,197	123,316	18,149	3.29E+08	-1.22349	3.365304

The shut-off damper displayed one of the more typical profiles after combining the data sets. It performed well in the Anderson-Darling test, yielding a value of 0.333 respectively. The kurtosis of the data set can best be exemplified in Appendix 17. The chart demonstrates a flat peak and this will account for the high kurtosis figure (such is the nature of the Monte Carlo simulation). The hybrid profile demonstrated a minimum lifetime of 53,625 hours, a mean lifetime of 123,316 hours and a maxima lifetime of 161,197. This translates into a minimum, mean and maximum life expectancy of 6.4, 14.8 and 19.3 years, respectively. The shut-off damper displays a narrower profile than some of its counterparts and this could be explained by the narrowness of the data set collected. The variance was found to be 3.29^{08} with a standard deviation of 18,149 hours.

6.6.10 Summary of Results

The following table provides a summary of the HCP-distribution curves (and the CIBSE-distribution curves) as well as the four options for modelling the part lifetimes presented, which have been converted into yearly figures for import into the life cycle model:

Table 34: Lifecycle distribution results table

	HCP Distribution		**Weibull Distribution**		**Triangular Distribution**		**Rayleigh Distribution**	
	Option 1		Option 2		Option 3		Option 4	
Part	Minimum Life (yrs)	Maximum Life (yrs)	Minimum Life (yrs)	Maximum Life (yrs)	Minimum Life (yrs)	Maximum Life (yrs)	Minimum Life (yrs)	Maximum Life (yrs)
Cooling & frost coil	1.3	21.2	1.5	25.6	2.7	24.1	2.4	36.2
Heating & Run around coil	2.6	22.9	2.6	25.9	4.3	23.4	3.4	36.6
Control Panel	10.0	25.0	10.0	18.6	10.6	18.4	10.1	37.3
Fan	2.5	21.6	2.8	25.7	3.1	23.5	2.8	35.9
Filter	n/a	n/a	0.1	1.7	0.1	1.7	0.1	2.4
Humidifier	8.6	14.0	8.6	19.0	8.8	10.9	8.7	25.8
Inverter	5.4	29.8	5.6	34.9	7.5	29.7	5.8	49.1
Motor	1.2	10.1	2.4	13.1	2.9	10.9	2.5	18.1
Shut-off damper	6.4	19.3	6.6	26.7	7.5	20.7	6.5	36.4
Silencer	n/a	n/a	5.3	43.5	5.8	38.5	5.7	60.1

Four alternative life cycle model profiles will be built using these four options. The results will be compared to the *current* profile which HCP is currently assigning funds to. This profile will be known as the current option, or *Option C*. In the instances where there is no lifetime guidance under the HCP distribution (filters and silencers), the Weibull distribution will be used in lieu.

In the next section, the created profiles of the four optional distributions will be compared against Option C: the current distribution. This distribution is what HCP currently has ‘planned’ for its air-handling units at HCP1. The current way of modelling is done on an AHU-level, is survey-led and proposes no part replacements. The results of this model currently form the basis of how much capital the company plans to set aside for the current year.

The part-costing exercise meant that an understanding of the variety of costs which can be found across the equipment parts inventory could be attained. Part costs were collected for all parts except for flatbank/polyseal filters and silencers. Although the distributions combined parts to form more accurate lifecycle profiles when actually creating the distributions, the part-cost data kept each part separate so that the cost of parts could be delineated. This led to a shallower sample set per part, but less distillation of the costs. The mean costs of the parts will be used in conjunction with the appropriate inflation index, for creating 4 lifecycle profiles. The result of these profiles will be a financial model which will indicate how much capital decision-makers should expect to spend within each financial year.

6.7 Part Costing

As part of the data collection process, costing for parts was undertaken with a view to creating more accurate costs for parts. A total of 101 cost samples were collected for parts. Not all the parts collected contained cost information and this is due to the way in which the data has been stored on each site. The breakdown of these costs can be seen in the table below. In previous studies (Kirkham, 2002) a method of data reduction was based on measuring the proximity in two-dimensional space between gross-floor area and cost. However, because of the nature of the assets being costed, there is no need for a £/m^2 metric or any other mode of comparison as they all form part of the same asset which is eventually measured in two-dimensional space on an asset level (i.e. AHU cost/m^2). Previous studies have also indicated where data-reduction techniques were necessary.

Motors exhibited the largest number of cost samples with no less than 44 data samples collected. No silencer failures were recorded, and as such, no cost data was recorded for this part. This is assumed to be because they are a non-moving part and have the highest recommended lifetime in CIBSE guidance. However, after contacting Allaway Acoustics, a well-known manufacturer of attenuators, a part cost of £228 was quoted based on the mean volume across the AHUs. The correspondence can be found in Appendix 18. There was also a lack of cost data for flatbank and polyseal filters; however, this is assumed to be due to the fact that because of their low cost and frequent replacement, they would be bracketed under planned-preventative maintenance and therefore should be excluded from lifecycle. The box-plots provide inter-quartile ranges which allows for conservative (Q3), balanced (mean), and optimistic (Q1) costs to be used in the lifecycle-modelling process. The maxima and minima data points will be ignored because of the large amounts of variance they display, particularly with regard to heating/cooling coils, fans and inverters, which are some of the more expensive components.

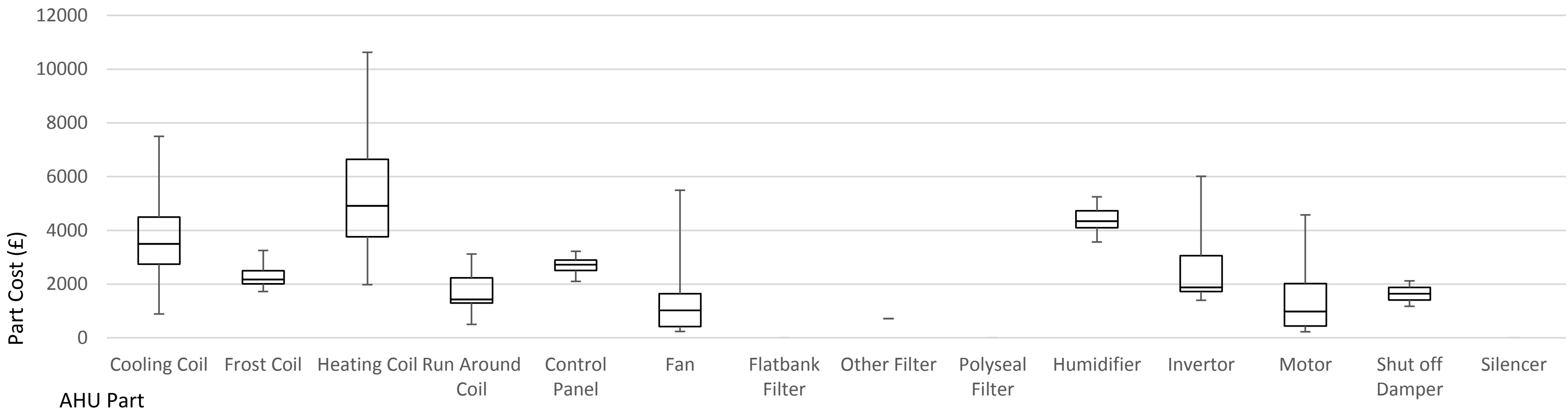


Figure 68: Interquartile cost-ranges for AHU components

Table 35: Box-plot of part cost data samples and descriptive statistics

	Cooling Coil	**Frost Coil**	**Heating Coil**	**Run Around Coil**	**Control Panel**	**Fan**	**Flatbank Filter**	**Other Filter**	**Polyseal Filter**	**Humidifier**	**Invertor**	**Motor**	**Shut-off Damper**	**Silencer**
Sample	5	4	6	5	4	16	0	1	0	5	13	44	2	0
Minimum	£887	£1730	£1980	£500	£2100	£233.54	n/a	£715.83	n/a	£3569	£1396	£225	£1171	n/a
Q1	£2746	£2007.5	£3760.25	£1295	£2508.75	£421.4225	n/a	£715.83	n/a	£4100	£1727	£445.7075	£1408.25	n/a
Median	£3500	£2175	£4915	£1430	£2720	£1027	n/a	£715.83	n/a	£4341.35	£1873.76	£980.25	£1645.5	n/a
Q3	£4500	£2500	£6641.25	£2230	£2900.97	£1646.385	n/a	£715.83	n/a	£4733.13	£3059.5	£2019.483	£1882.75	n/a
Maximum	£7500	£3250	£10625	£3120.02	£3218.88	£5490	n/a	£715.83	n/a	£5253	£6017	£4580.94	£2120	n/a
Sum	£19133	£9330	£33027	£8575.02	£10758.88	£22328.3	n/a	£715.83	n/a	£21996.48	£32297.02	£56807.18	£3291	n/a
Mean	£3826.6	£2332.5	£5504.5	£1715.004	£2689.72	£1395.519	n/a	£715.83	n/a	4399.296	2484.386	1291.072	£1645.5	n/a
Kurtosis	1.073337	2.294286	0.859801	-0.16484	1.07073	4.535223	n/a	n/a	n/a	-0.19925	4.319383	1.167901	n/a	n/a
Skewness	0.662701	1.314971	0.91071	0.429027	-0.37703	1.951585	n/a	n/a	n/a	0.096747	1.97195	1.198383	n/a	n/a
Variance	4772589	316418.8	7679303	794631.2	160215.9	1772107	n/a	0	n/a	324516.6	1517759	1021633	225150.3	n/a
St Dev	2184.626	562.5111	2771.156	891.4209	400.2698	1331.205	n/a	0	n/a	569.6636	1231.974	1010.759	474.5	n/a

The part costs do not include any on-costs such as labour. Therefore, recommended guidance from CIBSE and BCIS will be used in its place for taking this margin increase into account

6.8 The Life Cycle Model – Option Testing

6.8.1 Option C – the Current Model

HCP currently operates using the lifecycle model shown in Figure 3 (Option C). Option C is based on a non-intrusive survey of the AHUs at HCP1 and, as such, the resulting profile is an output of the predicted replacement pattern on an 'AHU level' (i.e. it does not suggest component replacement). The model indicates that £6,045,070 is to be spent across the 113 AHUs during the concession period. Some of the key drawbacks of this model are:

- **Level of detail:** Surveying non-intrusively means that they cannot explore the granular information pertaining to the parts within.
- **Operational realism:** The peak amount of lifecycle works occurring in one year is circa £2.1m. The practicality of delivering £2.1m worth of lifecycle replacement works for the AHUs is unrealistic (over £8,000 per day).
- **Spikes in model:** Spikes in lifecycle models affect the financial profile of the project from a financial perspective and can have significant impacts on how much money is extracted from the project at any given point in time by decision-makers.
- **Management Considerations:** The peak lifecycle expected in year 30-31 is flanked by two yearly periods with less than half the outgoings attributable to lifecycle (£721K and £567K). With space heating and ventilation expertise being a necessary pre-requisite for delivering the works operationally, this spike suggests an increase in personnel (leading to impacts on space within the operational FM team on site etc.) followed by personnel reductions after the peak tails off. Thus the model does not provide a picture which supports on-going business continuity.

Option C's profile can be seen in Figure 3 and will be compared statistically to the four options in the next section.

6.8.2 Options 1, 2, 3 & 4 – the PALM Profiles

The table below provides the key statistics on the lifecycle profiles. Option 4 provides the lowest profile until the end of the concession period (March 2048) and until the end of the hand-back period (March 2053 - £3.45m/£4.47m) followed by Option 1 (£3.88m/£4.71m), Option 3 (£4.31m/£4.86m) and Option 2 (£4.55m/£5.44m). Option C provided the highest profile at £6.05m irrespective of the concession and hand-back end dates. That is because of Option C's narrow AHU-level profile. The options produced a potential saving in lifecycle of just over £1.5m over the concession and hand-back periods depending on the decision-makers' choice of profile looking ahead. Figure 3 shows the cumulative impact of such a lifecycle model and further epitomises the differentials to be gained from life-cycling on a part/whole asset level. All options have the same parameters to allow for comparison, this being a compound inflation rate of 2.5% and an overheads percentage of 20%. The hand-back requirements (the assets which are predicted to be replaced within the five-year post contract completion) are a stark contrast, with Option C indicating there will be no works carried out during this period. Options 1, 2, 3 and 4 indicate lifecycle works of £820k, £888K, £545k and £1.02m (respectively) will be carried out. This is an important aspect to consider when modelling because contractually the facility should be handed back to the NHS trust in such a condition that no works will need to be carried out for the following 5 years. Where parts should be replaced, an agreement will be reached between both parties. It is likely that this will be a legal matter; however, assuming no works will need to be undertaken during this period is unrealistic.

Peak lifecycle expenditure within a year and the mean lifecycle cost on a pounds per square metre per annum metric (particularly during the concession period) are perhaps the most important figures in determining the suitability of a lifecycle predictive model. The Rayleigh-based optimistic profile demonstrated the lowest mean lifecycle/m^2/annum rate. This was just under £2/m^2/year and was the only profile to suggest a sub-£2 rate. The number of parts to be replaced during this period for each option can be found in Appendix 19. Options 1, 2 and 3 revealed a rate of £2.24, £2.62 and £2.48/m^2/annum, respectively. The current profile suggests a 175% higher rate that the optimistic profile, at nearly £3.50/m^2/annum. Under the part-based lifecycle model proposed, the minimum and maximum peak lifecycle expenditure in any one year ranges from £254k to £297k respectively. The details of the breakdown of where this cost is attributable for each option can be found in Appendix 20.

Table 36: Key statistics across all options

Option Scenario Test Results – Financial Output					
	Option 1 - Recommended	Option 2 - Conservative	Option 3 - Balanced	Option 4 – Optimistic	Option C – Current
Lifecycle Expenditure (Date -Mar 2048)	£ 3,889,325.00	£ 4,549,735.00	£ 4,316,696.00	£ 3,447,945.00	£6,045,470
Lifecycle Expenditure (Date -Mar 2053)	£ 4,709,546.00	£ 5,438,551.00	£ 4,862,476.00	£ 4,470,602.00	£6,045,470
Handback Requirements	£ 820,221.00	£ 888,816.00	£ 545,780.00	£ 1,022,657.00	£0
Mean Lifecycle / annum (Date -Mar 2048)	£ 117,858.33	£ 137,870.76	£ 130,808.97	£ 104,483.18	£183,196
Mean Lifecycle / annum (Date -Mar 2053)	£ 123,935.42	£ 143,119.76	£ 127,959.89	£ 117,647.42	£159,091
Mean Lifecycle /m2/annum (Date -Mar 2048)	£ 2.24	£ 2.62	£ 2.48	£ 1.98	£3.47

Mean Lifecycle /m2/annum (Date - Mar 2053)	£ 2.35	£ 2.71	£ 2.43	£ 2.23	£3.02
Peak Lifecycle Year	2039-40	2039-40	2046-47	2027-28	2030-31
Peak Lifecycle year foreseen expenditure	£ 271,046.00	£ 297,581.00	£ 284,373.00	£ 254,261.00	£2,099,212

Figure 71 to 74 illustrate stacked component graphs for each of the options. The profiles illustrate the costs associated with each part over time and, coupled with the top-level profile shown in Figure 69 and the crosstabs shown in Appendix 20, the decision-maker thus becomes empowered beyond what is offered by current practises because the model explains how each figure in year was reached. The sum total number of components to be replaced in options 1, 2, 3 and 4 are, 1984, 2303, 2110 and 1857, respectively.

The results have demonstrated that all four optional profiles produced a lower lifecycle cost across the whole of the concession period. The options produced a potential saving in lifecycle of just over £1.5m over the concession and hand-back periods depending on the decision-maker's choice of profile going looking ahead.

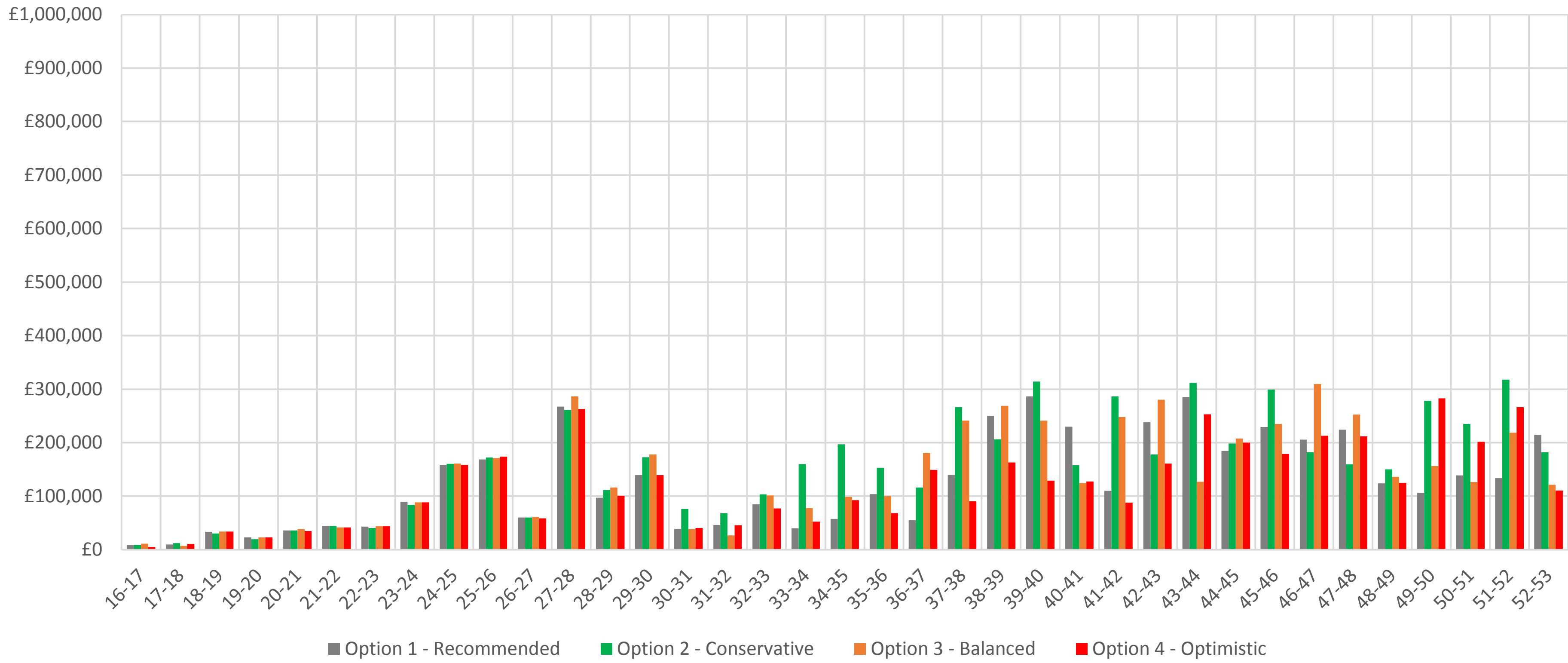


Figure 69: Alternative lifecycle funding profiles graph

Table 37: Alternative lifecycle funding profiles

	Year																	
Option	***16-17***	***17-18***	***18-19***	***19-20***	***20-21***	***21-22***	***22-23***	***23-24***	***24-25***	***25-26***	***26-27***	***27-28***	***28-29***	***29-30***	***30-31***	***31-32***	***32-33***	***33-34***
Option 1 - Recommended	£8,805	£9,691	£33,131	£23,193	£35,954	£44,281	£42,993	£89,220	£158,407	£168,437	£60,196	£267,378	£97,056	£139,420	£38,992	£46,127	£84,636	£39,991
Option 2 – Conservative	£8,805	£12,334	£30,487	£19,664	£35,954	£44,281	£40,340	£83,911	£160,179	£171,983	£60,196	£261,160	£111,318	£172,791	£76,060	£68,108	£103,318	£159,687
Option 3 – Balanced	£11,446	£7,048	£34,013	£23,193	£38,602	£41,630	£43,877	£88,335	£161,064	£171,096	£61,083	£286,550	£116,120	£177,723	£38,279	£26,454	£101,321	£77,670
Option 4 - Optimistic	£5,283	£10,572	£34,013	£23,193	£35,071	£41,630	£43,877	£88,335	£158,407	£173,756	£58,421	£262,937	£100,613	£139,420	£40,542	£45,852	£77,284	£52,443

Option	***34-35***	***35-36***	***36-37***	***37-38***	***38-39***	***39-40***	***40-41***	***41-42***	***42-43***	***43-44***	***44-45***	***45-46***	***46-47***	***47-48***	***48-49***	***49-50***	***50-51***	***51-52***	***52-53***
Option 1 - Recommended	£57,488	£103,859	£55,111	£139,905	£250,005	£286,277	£229,905	£110,015	£237,871	£284,974	£184,384	£229,104	£205,647	£224,331	£124,076	£106,227	£138,535	£133,576	£214,264
Option 2 – Conservative	£197,047	£153,118	£116,085	£266,414	£206,363	£314,304	£157,634	£286,321	£177,951	£311,421	£198,431	£299,292	£181,892	£159,353	£150,039	£278,140	£235,084	£317,875	£181,953
Option 3 – Balanced	£98,475	£100,060	£180,214	£241,226	£268,680	£241,179	£124,596	£247,891	£280,408	£127,206	£207,503	£234,747	£309,674	£252,266	£136,327	£156,055	£126,588	£218,761	£121,530
Option 4 - Optimistic	£92,366	£68,150	£149,000	£90,656	£162,748	£128,796	£127,543	£88,003	£160,949	£253,004	£199,999	£178,849	£213,108	£211,979	£124,851	£282,632	£201,548	£266,518	£110,615

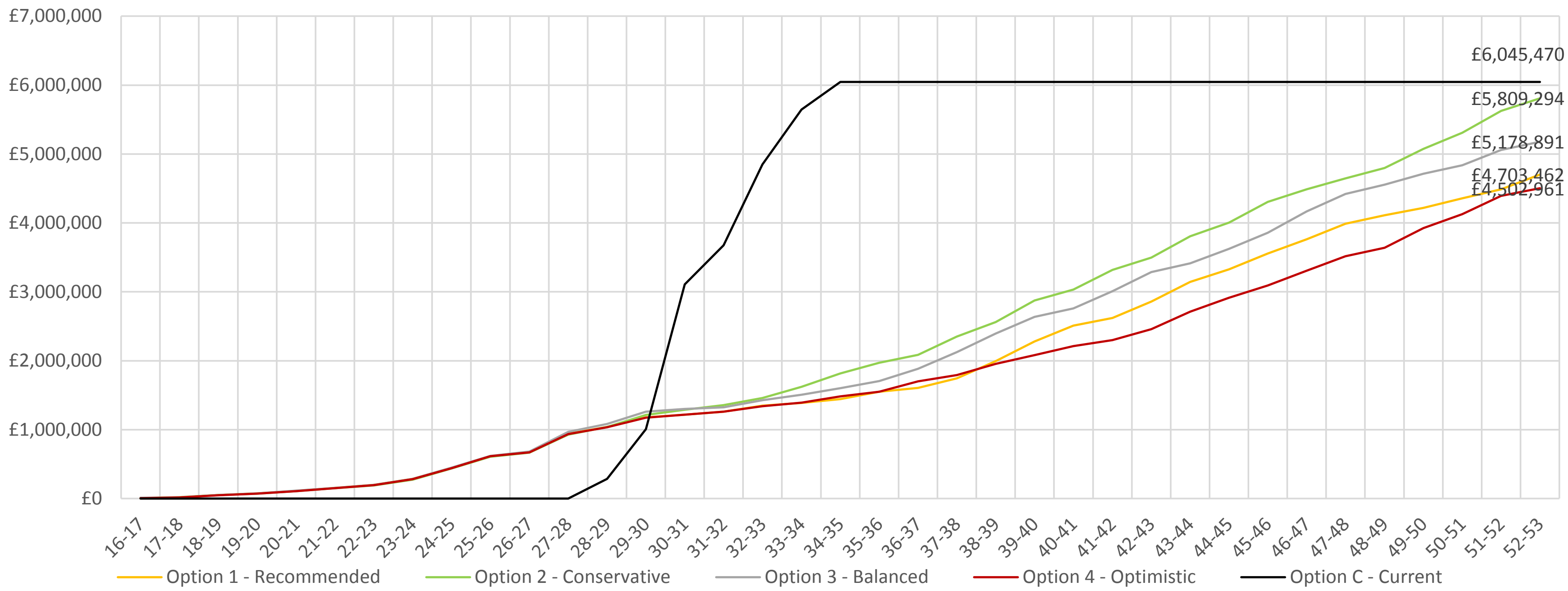


Figure 70: Cumulative profiles (Options 1,2,3,4 & C)

Table 38: Cumulative profiles table

	Year											
Option	***16-17***	***17-18***	***18-19***	***19-20***	***20-21***	***21-22***	***22-23***	***23-24***	***24-25***	***25-26***	***26-27***	***27-28***
Option 1 - Recommended	£8,805	£18,496	£51,627	£74,820	£110,775	£155,055	£198,048	£287,268	£445,675	£614,112	£674,308	£941,686
Option 2 – Conservative	£8,805	£21,139	£51,626	£71,290	£107,244	£151,525	£191,865	£275,776	£435,955	£607,937	£668,133	£929,293
Option 3 – Balanced	£11,446	£18,494	£52,507	£75,700	£114,303	£155,933	£199,810	£288,145	£449,210	£620,306	£681,389	£967,939
Option 4 - Optimistic	£5,283	£15,855	£49,868	£73,061	£108,132	£149,763	£193,640	£281,975	£440,382	£614,138	£672,559	£935,496

Option	***28-29***	***29-30***	***30-31***	***31-32***	***32-33***	***33-34***	***34-35***	***35-36***	***36-37***	***37-38***	***38-39***	***39-40***	***40-41***
Option 1 - Recommended	£1,038,743	£1,178,162	£1,217,154	£1,263,281	£1,347,917	£1,387,908	£1,445,396	£1,549,255	£1,604,366	£1,744,271	£1,994,276	£2,280,553	£2,510,458
Option 2 – Conservative	£1,040,612	£1,213,402	£1,289,462	£1,357,571	£1,460,889	£1,620,576	£1,817,624	£1,970,742	£2,086,827	£2,353,240	£2,559,603	£2,873,907	£3,031,541
Option 3 – Balanced	£1,084,059	£1,261,782	£1,300,060	£1,326,514	£1,427,835	£1,505,506	£1,603,981	£1,704,041	£1,884,255	£2,125,481	£2,394,161	£2,635,340	£2,759,935
Option 4 - Optimistic	£1,036,109	£1,175,529	£1,216,071	£1,261,923	£1,339,207	£1,391,649	£1,484,015	£1,552,165	£1,701,165	£1,791,821	£1,954,569	£2,083,365	£2,210,908

Option	***41-42***	***42-43***	***43-44***	***44-45***	***45-46***	***46-47***	***47-48***	***48-49***	***49-50***	***50-51***	***51-52***	***52-53***
Option 1 - Recommended	£2,620,473	£2,858,344	£3,143,318	£3,327,702	£3,556,806	£3,762,453	£3,986,784	£4,110,860	£4,217,087	£4,355,622	£4,489,198	£4,703,462
Option 2 – Conservative	£3,317,861	£3,495,813	£3,807,234	£4,005,665	£4,304,957	£4,486,849	£4,646,203	£4,796,242	£5,074,382	£5,309,466	£5,627,341	£5,809,294
Option 3 – Balanced	£3,007,827	£3,288,234	£3,415,440	£3,622,943	£3,857,690	£4,167,364	£4,419,630	£4,555,957	£4,712,012	£4,838,600	£5,057,361	£5,178,891
Option 4 - Optimistic	£2,298,910	£2,459,860	£2,712,863	£2,912,862	£3,091,710	£3,304,819	£3,516,798	£3,641,648	£3,924,280	£4,125,828	£4,392,346	£4,502,961

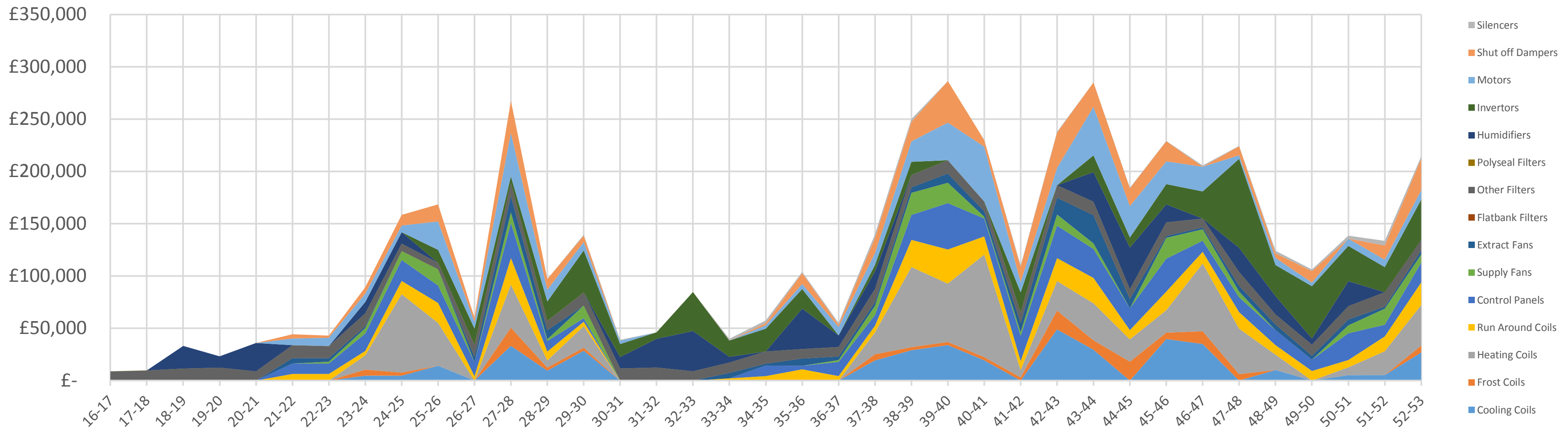


Figure 71: Option 1 -Recommended lifecycle profile stacked component graph

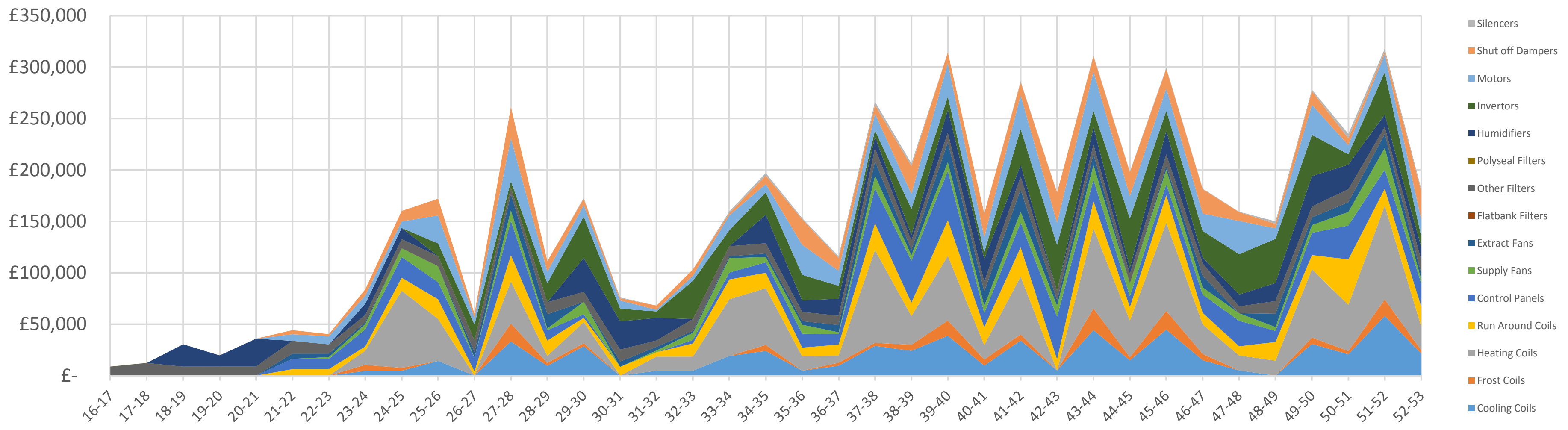


Figure 72: Option 2 -Conservative lifecycle profile stacked component graph

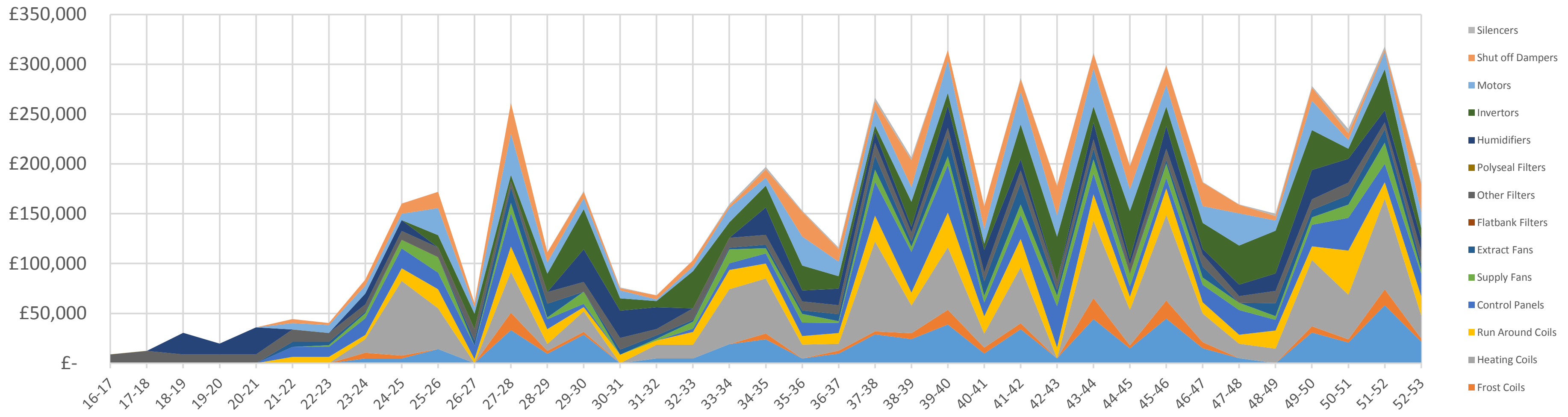


Figure 73: Option 3 -Balanced lifecycle profile stacked component graph

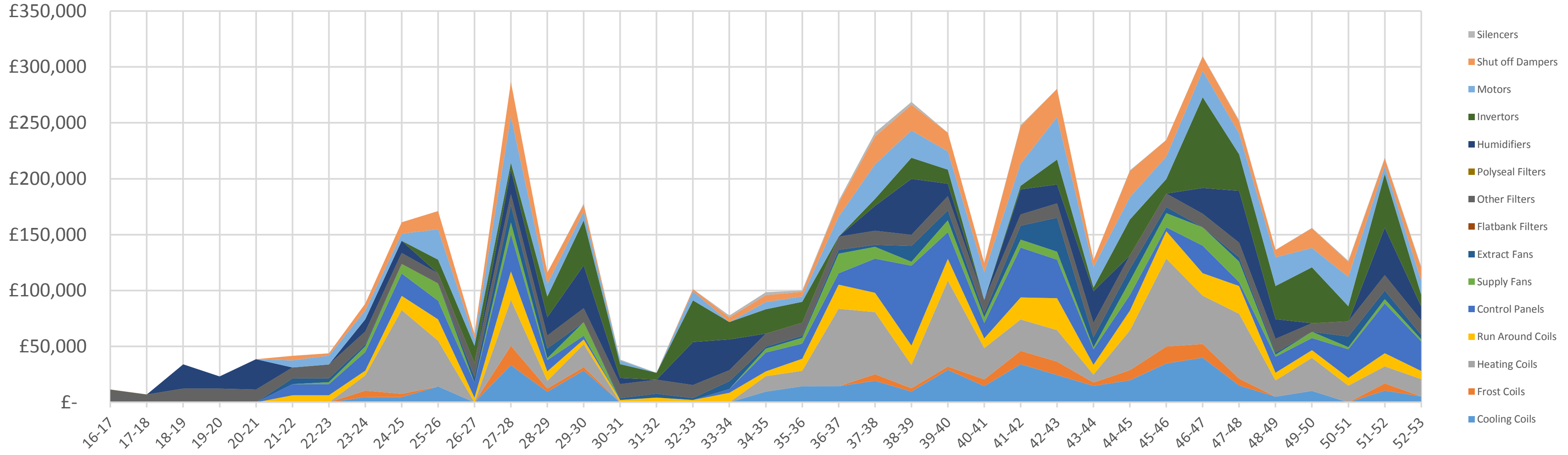


Figure 74: Option 4 -Optimistic lifecycle profile stacked component graph

6.9 Summary

This chapter began by presenting the results of the financial and engineering-based risk profiling of the air-handling units at HCP1. During the engineering-risk survey, it was found that the AHUs fell into a risk range of between 11% (AHU 30E) and 82% (AHUs 02S, 06S and 23AS). In terms of contractual risk, those AHUs serving critical areas such as operating theatres or cardiac wards were high on the paymech risk with tens of thousands of pounds of fines attributable for a failure ofone period (8 hours).

This chapter also presented the results of the distribution modelling using CIBSE and HCP data as inputs to create four optional profiles for part-based lifecycle modelling.

- Option 1: HCP distribution – these distributions were seen as the recommended option. The distributions were formed through understanding the distribution of the data samples collected from the HCP hospitals before fitting an appropriate simulated distribution to make up the number of parts yet to fail. The hybrid distributions utilised the normal distribution and Weibull distribution. Overall, more than 150 data samples were collected across the various AHU components.
- Option 2: Weibull distribution – these distributions were seen as the conservative option and most risk averse of the three CIBSE-based optional distributions because of the Weibull's natural shape and strong negative skewness, indicating a heavy front loading of failures for each part.
- Option 3: Triangular distribution – these distributions were seen as a balanced alternative option because of the Triangular distributions natural asymmetry. Also, the inputs to the distribution were simpler to deduce (those being the minimum, maximum and mean values).
- Option 4: Rayleigh distribution – these distributions were seen as the optimistic option because, while being front loaded and displaying a high kurtosis, the alpha value was the only input to the model, leaving very little room to optimise the shape of the curve. This option is seen as the most similar to the CIBSE figures because the mean lifetime of the parts recommended by CIBSE form the only input to the distribution. This is the only option for which this occurs.

The lifecycle model compared the four optional distributions with the current modelling approach adopted by HCP. The survey-led approach was found to be lacking in clarity because of its dearth of granularity in that it did not disclose part replacements.

- Results showed a lifecycle expenditure of between £3.45m and £4.54m (options 1-4) compared to the current £6.045m (option C).
- A reduction in lifecycle/m2/annum of over £1.
- A peak lifecycle expenditure in any given year almost 90% smaller than option C suggests.

The AHU-level model proposed a schedule of up to over £2m of lifecycle works within one year, over 5 times more than the average maximum across the four optional profiles. The issue of clarity regarding proposals as to what is to be replaced was discussed and optional models 1-4 provided a far smoother, more robust lifecycle-budgeting plan due to the fact that each part replacement for each AHU was quantified.

Other points of note are:

- Almost all of the data collected from HCP sites suggests a normal distribution based on the Anderson-Darling statistics.
- Zero silencers were recorded to have failed across the hospitals.
- The heating coil showed the largest variance in part cost – ranging from circa £2,000 to over £10,000.

Chapter 7. PALM's Impact on Decision-Making

Following the completion of the Lifecycle Costing and geometrical model, a two-part qualitative feedback process was undertaken. This chapter presents an overview of the method used and analysis of the qualitative data was assembled. key industry professionals' perceptions of the model and its impact on and implications for business is described.

7.1 Introduction: Two-Stage Qualitative Feedback

The two-stage qualitative feedback process consisted of the ***HCP Management Board meeting*** (stage 1) and ***qualitative interviews*** (stage 2).

7.1.1 Stage 1: HCP Management Board Meeting

On Tuesday 8 December 2015, the research was presented to the same HCP Management Board which sanctioned the data-collection exercise. The outputs presented to the Board comprised those items shown in the *PALM outputs* box in the PALM-architecture diagram (see Figure 36). The Management Board consisted of the following:

- Chief Executive Officer (CEO), HCP
- Chief Financial Officer (CFO), HCP
- Managing Director (MD), HCP
- Business Development Director (BDD), HCP
- Regional Director South (RDS), HCP
- Regional Director Midlands (RDM), HCP
- Regional Director North (RDN), HCP

The presentation lasted 60 minutes and was agenda Item 2 in the December Management Board meeting. The model was then presented, along with a promotional video for PALM (see Appendix 21), before a recorded discussion on their feelings towards the visual representation of PALM took place. All the board members fulfil the criteria of decision-maker and therefore fit the desired interview target population.

7.1.2 Stage 2: Qualitative Interviews

Using comments made during Stage 1 as a cue for questions, a series of interviews was set up with the CEO, BDD and RDS. Perhaps the most important interview in this instance was not the one with the CEO but with the RDS, as HCP1 is a project under his authority. These groups are considered Key Informants according to Daskalova (2008) and Raslan (2010) who, by definition, have valuable information which provides insight on the function which is being interrogated as a result of their knowledge, experience and specialist skills. Specialist skills (in this instance) being the ability to provide expertise in judging the usefulness and value of the PALM visualisation to HCP as a business.

7.1.3 Study Preparation and Interview Design

In preparation for the interviews, two day-courses in social research were undertaken at the University of Surrey on 27 January 2014 and 4 February 2014; these courses covered Qualitative interviewing (by Dr Nicola Green and Dr Sue Venn) and 'Thematic analysis of Qualitative Data (by Dr Carrie Dunn and Dr Sophie Sarre). The interviews were based on a standardised open-ended approach (Tashakkori & Teddlie, 2003).

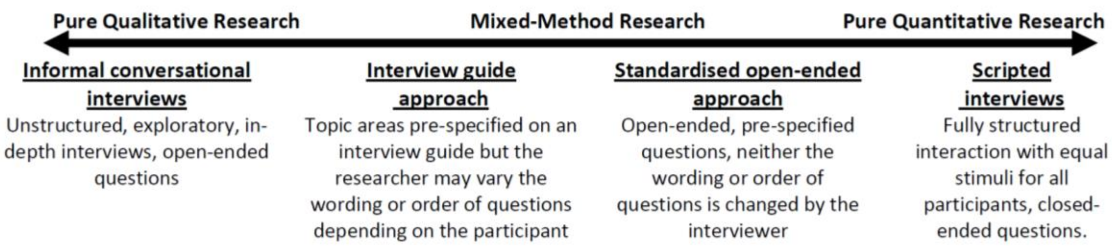


Figure 75: Types of research interviews (Tashakkori & Teddlie, 2003)

Previous research has outlined a two-part framework for interviews (King, 1994); that is, an introductory session followed by a sanctioned question section. The interview schedule consisted of eight open-ended questions. Open-ended questions were used throughout the schedule because this allowed the participants to contribute and elaborate on their personal experiences of asset management and lifecycle modelling. The schedule can be found in Appendix 22.

7.1.3.1 Sampling

It was not anticipated that the entire Board would agree to be interviewed due to geographical or time-related constraints. The nature and context of the research participant population meant that the representative group would almost certainly be representative of the population. So all three individuals interviewed (CEO, BDD, RDS) constituted Key Informant status and 43% of the Board (Daskalova, 2008).

7.1.3.2 Ethical Position

Because all interviewees were members of the sponsoring company, there was no risk to the public with regard to data protection. The nature of the research was such that no undue stress was placed on any participant and their identities will be safeguarded. The participants gave their permission for the interview to be recorded during Stage 1.

7.1.3.3 Interview Recording and Transcription

The interviews were recorded using a digital voice recorder. The recordings were transferred onto computer for analysis and deleted from the recorder. In this research the transcription of the interviews was made verbatim to provide an accurate record of the thoughts of the participants. The audio files were transcribed by the researcher in accordance with the transcription conventions outlined by Gibbs (2007). The full interview transcripts are included in Appendix 23.

7.2 Data Analysis and Results

Tesch (1990) describes common features of approaches to analysing qualitative data in two ways: data similarities and analysis similarities. Data should be segmented meaningfully while retaining connections to the whole. The analysis of such data should be cyclical, reflective and inductive (Tesch, 1990). Thematic analysis was used to gauge the participants' responses and feelings towards the PALM visualisation. Thematic analysis was chosen because it was deemed to be the clearest way of comparing feedback on one theme between a small number of participants. Based on the targeted research objectives and responses from the participants, the following 'themes' were identified from the interviews:

- Improving lifecycle confidence and understanding
- Improving decision-making
- Informing other areas of asset management
- An attractive business proposition looking ahead

The key findings are presented below (verbatim) and have been incorporated into a single narrative based on an organisational approach suggested by King (1998).

Table 39: Thematic chart

	Interviewee		
Theme	I01 Regional Director South	I02 Business Dev. Director	I03 Chief Executive Officer
Increasing lifecycle confidence and understanding	*For someone from a non-technical background like me I can walk into a plant room and see a big box that's an air-handling unit. What goes on behind that is an absolute dark art to me. All the component bits… I can see that yes, there's component parts here that do make up the sum. In reality I can picture that now as well, that actually that motor's 5 years, those fans are 12 years and what-have-you.*	*I'm not a technical person, but having an understanding of what an air-handling unit actually looks like and what these subcomponents actually look like, the context in which they placed, some of the issues which may be given rise to their replacement I think is informative and very useful. And perhaps also just understanding the quantities involved, not from a financial perspective but from a simple quantity perspective.* *I think you gave me the knowledge of how extensive that system really is which I think enhances the*	*…what does surprise me is that CIBSE provides guidance to such a level of detail. Well I think it better informs it because you're starting to get out a theory and you're starting to go down into the detail and it's backed up by actual information.* *I do think that it would help with regards to the funders so the actual banks rather than the TAs. But again from a TAs perspective maybe it's a tool he can use in convincing and talking with his bosses who are the funders so I think as I say, I see it as not an end*

		investors and decision-makers' appreciation of some of the complexities in decision-making. It's not just one unit or a series, it's actually a whole system you need to consider.	*in itself but as an aid in the whole process about giving confidence.*
Improving decision-making	*I can start to see how decision-making can be made on fact rather than gut feel. I think the world we are moving into is much more based around evidence, and giving boards comfort that the evidence is there to take money out and the more we can add to that evidence base the better.*	*I think as an investor or decision-maker I would probably expect to have the summary of the analytics presented to me first so that the assumptions and wider parameters of the capex investment are made explicit before. I think then the visualisation enhances where exactly there is impact within the wider system and it may also enhance your understanding of what the subcomponents are saying according to the investment choice.*	*…the consequence of what we're looking at here (picks up cumulative lifecycle chart – figure 104) is that A, we are removing the big area of expenditure currently in the model, so from a cash flow point of view it looks much better and secondly then the actually from a cumulative point of view you've got more than a marginal saving you've got a £1m saving there. So what 15-20% saving by doing it that way*
Informing other areas of asset management	*the model itself brings currently what's done in disparate parts together to one point and what I mean by that is that if you look at lots of different elements that need to be replaced over time there must be a point where if you keep replacing the component parts you begin to ask whether you should carry on patching this up or should you just go out and buy a new one. I think the model you're starting to bring together shows a lot of that information in a cohesive way rather than what we've got at the moment which is very experienced people out there that know intuitively but if you ask them to evidence it, it would be quite difficult.*	*If you go out and ask an operator on the floor at [redacted] looking after AHUs could they articulate a current need at this time? I suspect not. Could you present them with something and then they would understand their need? Probably yes… this should form part of an operational BIM visualisation model, I think that would be powerful. I haven't seen any such models but I think it would be quite interesting to develop that capability and integration between the two because then it makes everything very real. What do I need to do? Here's my plan for today. How do I replace that component?*	*So say we've assumed said failure of said points, in future you can assess whether this was correct and if not what the other bits and pieces which actually fail sooner are. So from a critical spares point of view, we'll know what parts we need to hold.*
Technological advancement and business proposition going forwards	*I think there is something clearly there about if no-one else is doing this there's got to be a USP to get out there. If we could find a way to sell that as a product and demonstrate that there is more evidence and assurance around some of this stuff, not just in stripping out lifecycle, but those organisations that are non-PFI and don't actually have a lifecycle pot but more a lifecycle budget. I think it's positive for HCP on a number of levels. 1, it retains MSAs. 2, it increased our position in the market*	*I think the visualisation brings home some of the technical complexities. My concern is the amount of time it takes to generate the visuals. But there's no doubt that if you can develop a visual model of an entire building or subset of the 10 most critical assets… I think that would be a powerful message because you can't visualise something unless you have a very intricate and robust data set and that speaks volumes to people who might contemplate taking on the services of HCP.*	*I mean I think from a selling point of view I think it's ideal. It's great.* *In time it could be the sort of vehicle that…the core in which you could potentially start adding things on around it, whereas at the moment it's part of it, in time it's actually the core of it and you're adding stuff so it actually is the main driving engine*

7.2.1 PALM's Ability to Improve Confidence and Understanding in Lifecycle Planning

Visual modelling was reported to improve lifecycle confidence and understanding, according to the participants. While I01 and I02 stated they lacked technical know-how, it was stated that the model helped them understand how extensive the system was (I02) as well as illustrating how the concept of modelling on a more granular level is carried out. I03 specifically mentioned the increasing confidence levels of those stakeholders not directly linked with HCP. The key points to come out of this area are:

- The model can improve the understanding – particularly from a non-technical point of view.
- Understanding is not confined to the HCP Board but applies to external stakeholders as well.

7.2.2 PALM's Ability to Improve Decision-Making

The overall impression gained from the interviews was that the model did improve decision-making. Although, it is important to view the tool as a part of the whole process, not the entire focal point, with I02 suggesting a marriage between the model and analytical summary of the figures, in tandem. I03 noted that the cash-flow position looked stronger according to the model and the analytical summary of the figures too. He accepted that the model yielded a large saving and described the financial position as 'looking much better'. I01 saw the tool as being part of a larger evidence base and a step away from 'gut feel' surveying methods. The key points to come out of this area are:

- Decision-making can be improved but it is important not to overstate the reliance on hard data.
- Board members feel more confident in the lifecycle prediction when they can physically see and pair together the replacement schedule figures and model.

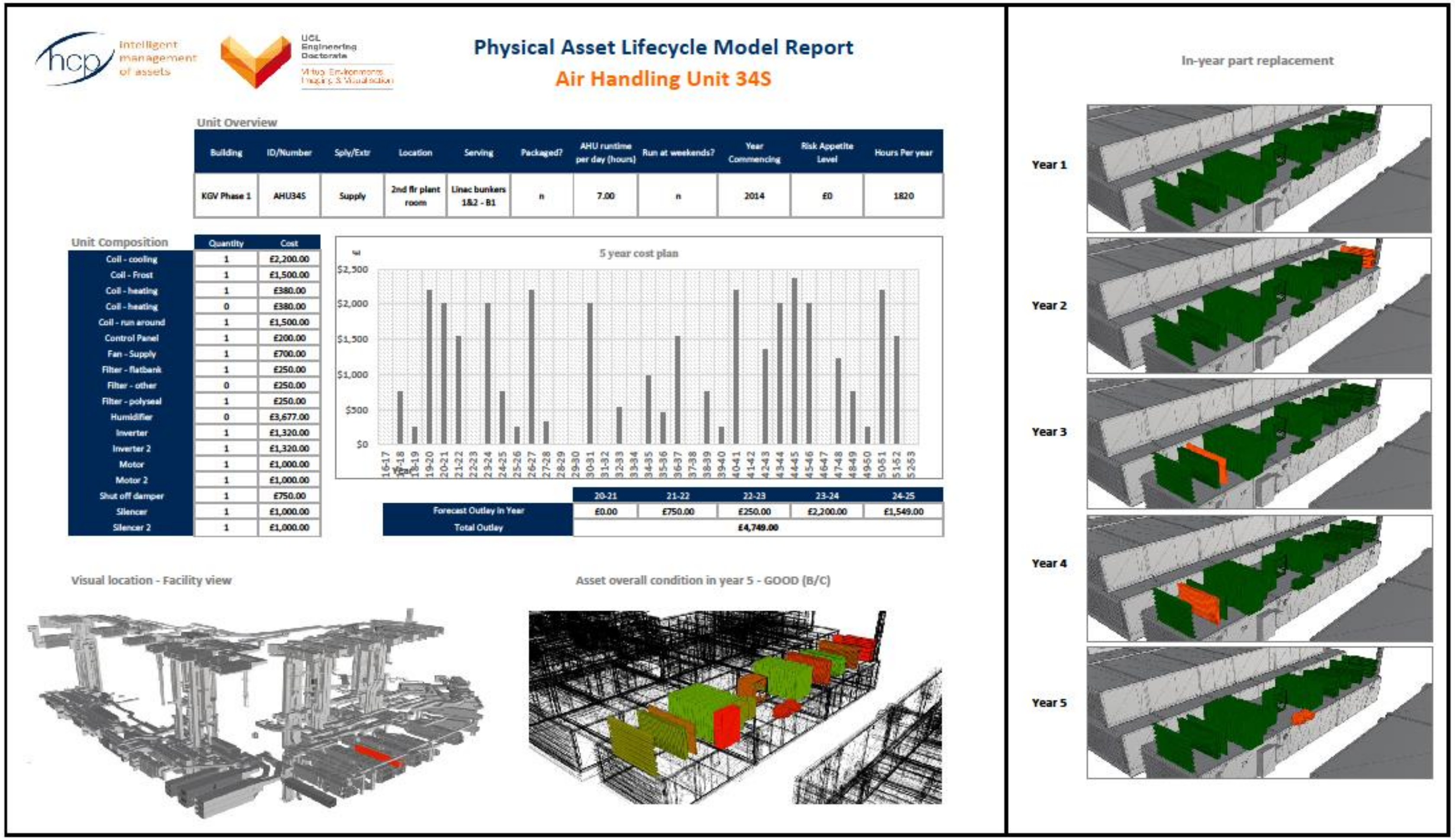


Figure 76: Example PALM model report output

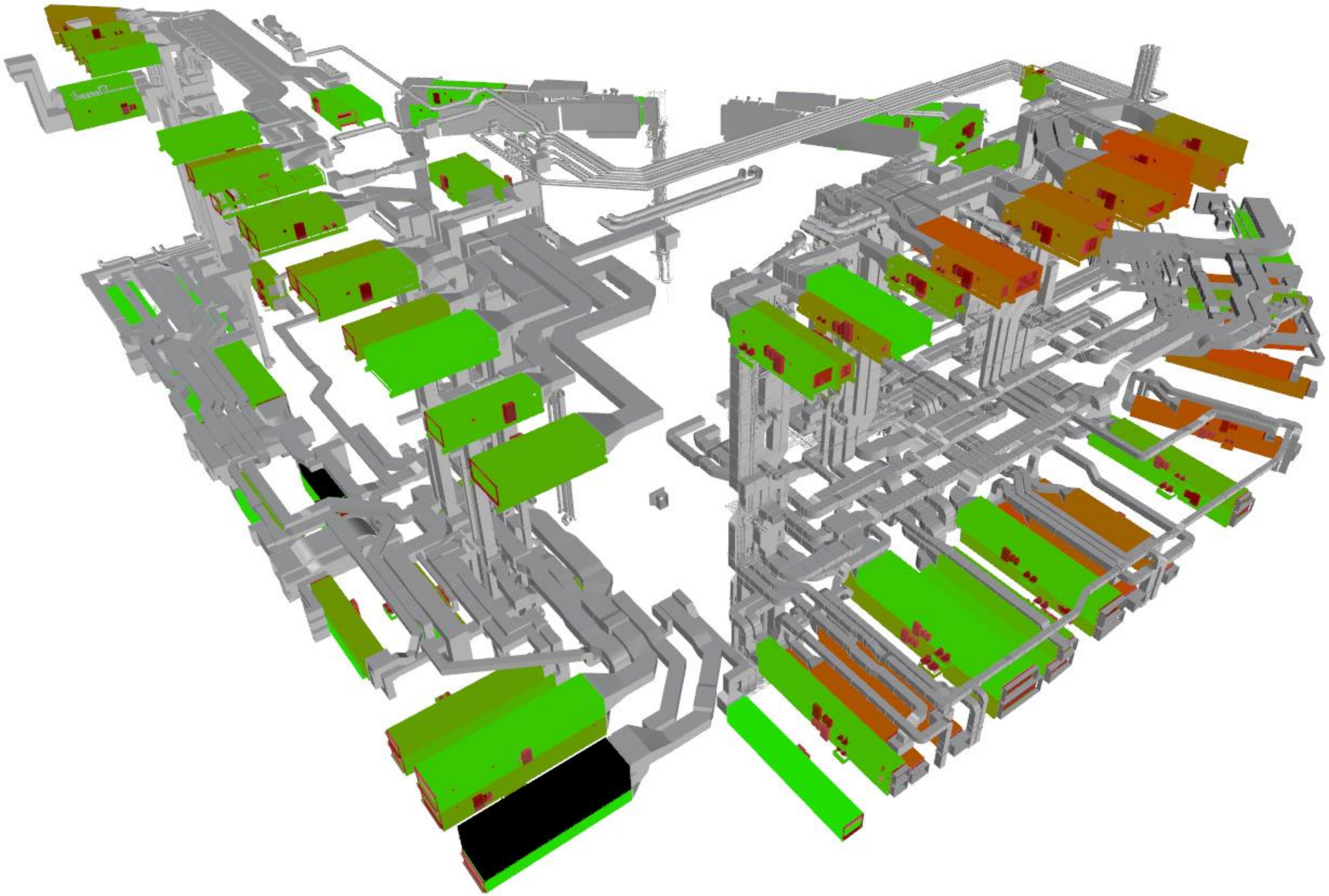


Figure 77: AHU Risk level visualisation (Stream 1)

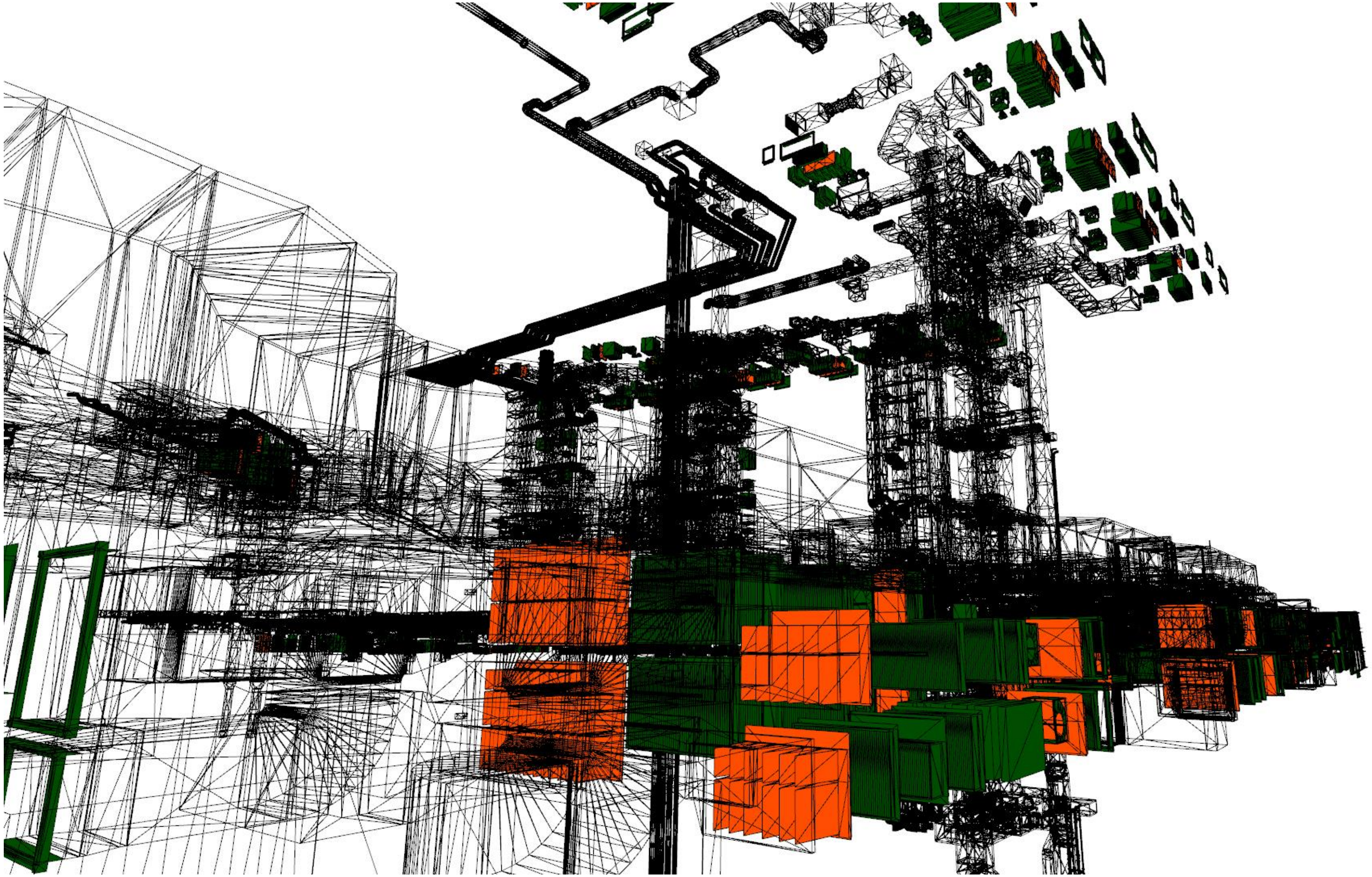


Figure 78: AHU Component level view (Stream 2 -AHU system component replacement viewer -linked to lifecycle model)

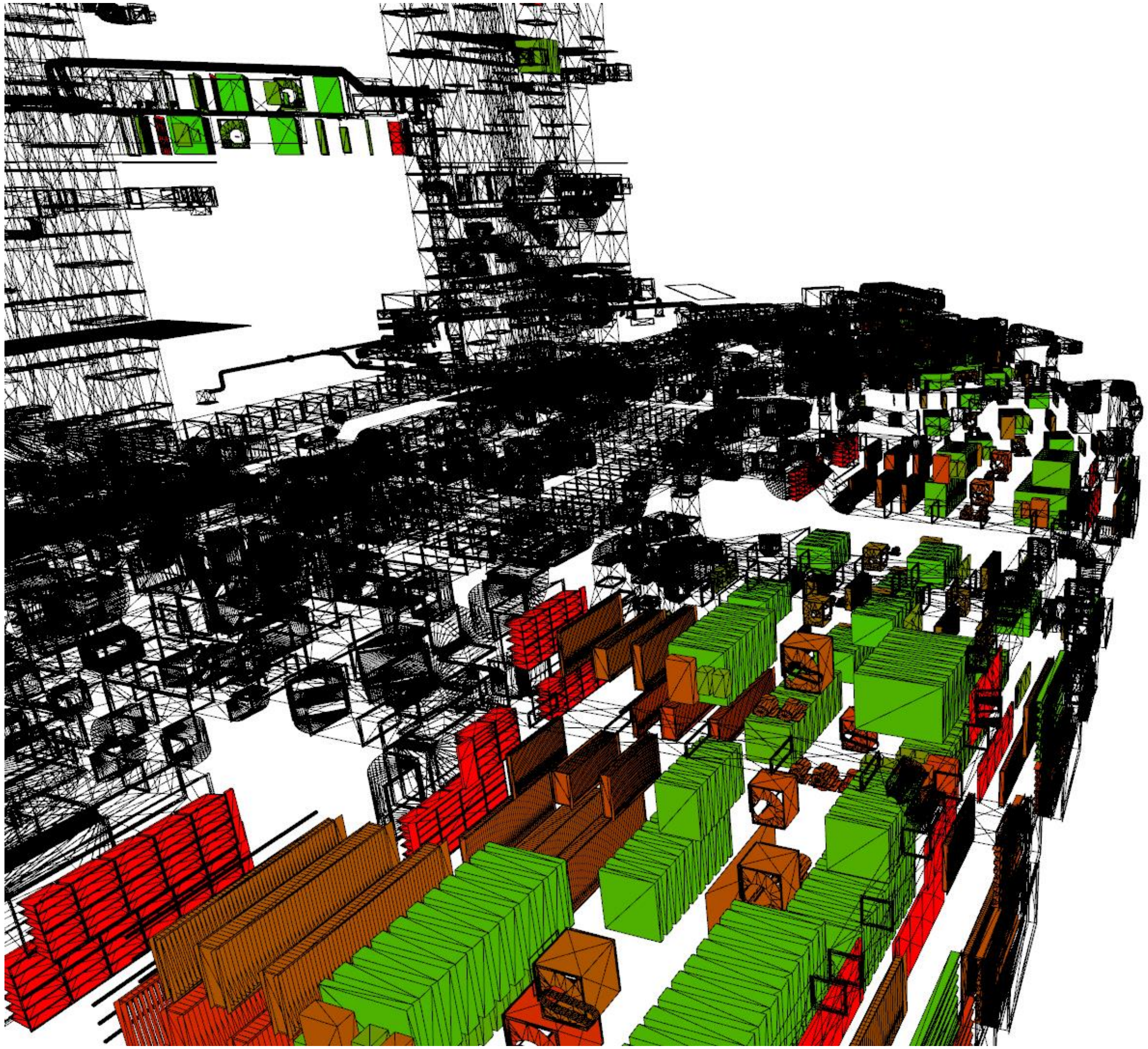


Figure 79: AHU Component level view (Stream 3 -AHU gradient system component replacement viewer -linked to lifecycle model)

7.2.3 PALM's Ability to Inform Other Areas of Asset Management

The experience of the Board members yielded some unexpected results and this meant the utility of the tool could be cross-examined in terms of its application to other areas of asset management. I01 viewed the tool as something convergent, merging various stages and disciplines into the one tool. I03 was more divergent in his thought processes and considered the implications of such a model on the basis of functional obsolescence and critical spares holdings. These are areas outside the scope of the thesis but which the model does inadvertently cover through categorising risk. I02 viewed the tool as being useful on an operational level and saw the benefits that such a model could deliver to those whose job it was to physically replace the assets on site. The key points to come out of this area are:

- Senior decision-makers are becoming more aware of the operational implications of a lifecycle model through seeing part replacement strategies presented visually.
- The model can be adapted in future for a different but equally critical asset-management business area such as functional obsolescence.

7.2.4 PALM's Ability to Provide Technological Advancement and a Business Proposition

There was open acceptance of the tool's ability to bolster business revenues in the future. I01 discussed the possibility of looking beyond the PFI sector, at non-PFI areas of interest which have not currently been unexplored by HCP. Since its inception, it has solely been centred on PFI projects. Demonstrating the research was viewed as having enhanced the image of HCP's technical capability, and there is an appreciation that in time it could be the hub of the life cycle modelling method. It was described as having the potential to be the main 'driving engine' (I03) for the business. The key points to come out of this area are:

- The demonstration of such a tool has rarely been seen and as such, will provide HCP with a competitive edge in the PFI marketplace.
- The future of lifecycle modelling could rely on such approaches from here onwards.
- The model can be integrated into HCP's business proposals for new and existing clients in PFI and beyond.

Figure 76 illustrates an example report of output based on PALM.

7.3 Summary

In the context of the study, a two-stage qualitative data-gathering exercise was undertaken. The first stage involved presenting the model and findings to the HCP Management Board. The second stage involved inviting the Board to be interviewed in order to assess their views on PALM and approach.

The interviews and questions were based on the feedback gained from the Board meeting and, as part of the approach, all the questions were open-ended. A thematic analysis of the results was presented and the key themes identified were:

- Improving lifecycle confidence and understanding
- Improving decision-making
- Informing other areas of asset management
- An attractive business proposition looking ahead

The main findings of the interviews were:

- The model can improve the understanding – particularly from a non-technical point of view.
- Understanding is not confined to the HCP Board but applies to external stakeholders as well.
- Decision-making can be improved, but it is important not to overstate the reliance on hard data.
- Board members feel more confident in the lifecycle prediction when they can physically see and pair together the replacement schedule figures and model.
- Senior decision-makers are becoming more aware of the operational implications of a lifecycle model through seeing part replacement strategies presented visually.
- The model can be adapted in future for a different but equally critical asset-management business area, such as functional obsolescence.
- The tool has rarely been demonstrated before and as such, will give HCP a competitive advantage over its rivals in the PFI marketplace.
- The future of lifecycle modelling could rely on such modelling approaches looking ahead.
- The model could become an integral part of HCP's business proposals for new and existing clients in PFI and beyond.

Some of the issues with the visual modelling approach are:

- Age-based limitations and a reluctance to change.
- Time spent in modelling the assets to make it a viable tool for using on a day-to-day basis.

Chapter 8. Discussion

Life cycle modelling of complex assets in the PFI healthcare sector is currently based on a non-intrusive type survey. By nature, these surveys fail to adequately assess and quantify risk because the forecasts for replacing such assets are done on an asset level. Such an approach ignores the fact that each asset (in the case of air-handling units) has a number of components, each with differing life expectancies. The field of asset management is still evolving, with norms such as PAS 55 setting higher standards than ever, and coupled with new methods of aggregating assets through nomenclatures such as NRM3, the discipline is showing marked steps of improvement. The idea of modelling for future expenditure is something which is currently being undertaken, and this is particularly relevant in the field of PFI where contracts between the public and private sectors define long-term windows of responsibility. Chapter 1 describes the PFI contractual structure and it was explained that life cycle provides the largest grey area in terms of future business forecasting because of the lack of data which can be utilised for predicting failure. However, this also makes asset management and lifecycle modelling the most favourable area of research in PFI because of the financial rewards it offers those who can predict their future expenditure with greater accuracy. In the PFI field, accreditation to standards such as ISO 55000 is rare and, while producing this research, HCP has been awarded ISO 55000 accreditation, a sign that management service providers are continually striving to improve the quality of service to clients. However, data beyond the condition survey is scarce. Market tools such as VFA, Manhattan Atrium and others claim to provide the solution to empowering decision-makers, but there is still little evidence to prove that a business model can be built around such tools. @Risk is a piece of commercial software which still places trust in the ingenuity of the user to produce meaningful output

With regard to visualisation, there is little to no research which looks beyond BIM as the tool for better informing decision-makers on budgeting for assets. Models discussed in Chapter 4 have already shown the complexity of bridging the data gap between BIM in the construction phase and facilities management. Perhaps the answer lies beyond the IFC schema for the PFI asset-management profession. Generative design modelling displayed by tools such as Rhino5 sidesteps the barriers to the extraction of IFC information because not all of the data contained in industry foundation classes are necessary beyond construction. Coupled with the reality that decisions on life cycle are made in a matter of minutes, questions should be asked as to the suitability of some data-exchange schemas currently on offer. Narrow BIM appears to offer a healthy depth of information for strategic digestion and Rhino5 facilitates the interoperability of BIM during the operation lifecycle stage.

8.1 A Comparison with Other Lifecycle and Visual Models

The research project has presented an original approach to life cycle costing and the visualisation of life cycle replacement strategic plans. The current approach adopted in the industry places the onus for competent lifecycle modelling with the surveying teams. The proposed model draws on areas of research presented in the literature through works such as Lair and Chevalier's (2002) *belief*, *probable* and *plausible* distribution curves (Options 2,3 and 4) and combines the distribution modelling with risk tools from Hurst (2005) and ISO standards to give aggregation to assets currently viewed as being almost identical in terms of lifecycle. While aspects of Hurst's model were used in the study, one potential improvement on this method may be to pair the proforma approach with an hourly-based, rather than annual-based, quantitative method. This would increase the accuracy of the predictive model and take into account the fact that while lifecycle models produce year-on-year costs, on an operational level this equipment is actually run on a daily basis. Ujjawls (2012) normal distributed damage-mechanism approach assesses the annual probability of failure over time and truncates these values. The truncation approach is based on previous work (Balasooriya, 1995; Wu et al., 2013) and a similar approach to distribution based on CIBSE guidance and real data (rather than corrosion rates) was adopted (Ujjwal, 2012). The visualisation draws on previous research and its subsequent drawbacks in capturing facility geometry. The difficulties are highlighted in research by Murphy, McGovern and Pavia (2009). Using existing geometry, Shen, Hao and Xue (2012), and Motamendi (2014) describe some of the drawbacks of IFC-schema import and current BIM modelling tools as well. Wu and Shih (2014) describe some of the key advantages and advocate the use of Rhino5 and Grasshopper as a set of tools for supporting the visualisation of geometry to provide information. In their model, the conveyance of heat-gains, structural form and cost was described.

Life cycle modelling on an asset level leads to work deferrals because there is no understanding of asset management on a specific part level. Woodhouse noted that the business impact of deferring expenditure or different projects is rarely quantified, yet is essential to systematically demonstrate and manage the different priorities for competing investment options (Woodhouse, 2012). The PALM alternative adopts similar emergent views on lifecycle modelling as those described in Bowden and Zhu's multi-variance analysis (2010). That is, that models boasting flexibility through the use of user-defined preferences (such as the conservative balanced, recommended and optimistic risk-appetite levels) are superior.

The PALM framework is an amalgamation of previously unlinked aspects of lifecycle modelling. CIBSE (2008) defined the four main elements of operational risk and PALM does delivers improved decision-making capabilities, while retaining and making the information associated with these four main elements more transparent. Risk alignment, discussed by Conachy (2008), looks at how the reallocation of resources outperforms current blanket methods and the research actually follows this trajectory. Woodhouse's (2012) uncertainty parameters (*variable deterioration rates*, *quality of measurement* and *variable usage*) have been considered throughout modelling asset-specific runtimes and the more detailed levels of surveying.

8.2 Specific Contribution to Knowledge

The research demonstrates the development and testing of an original framework for the life cycle costing of air-handling units within an NHS healthcare facility. The life cycle model presented means that decision-makers will actually be able to assess the likely long-term costs of asset part-replacement, based on physical condition, contractual risk and probabilistic modelling of failure rates. PALM has made the following advances which supersede those of the previous models within the PFI Asset Management field:

- The model presented is a first attempt at creating a research project which yields improved knowledge on future replacements of previously un-surveyed parts, using real data collected across PFI healthcare projects. The lack of validation is conceded as the model which would take a considerable amount of time to truly validate. However, with this being said, the validity of the results as a result of testing remains unaffected.
- An innovative framework with a bespoke understanding of the case-study healthcare facility. The framework utilises the surveying skill-sets currently used by MSPs such as HCP but focuses on assessing the asset risk rather than life prediction. The weighted model is coupled with a unique understanding of the financial consequences to the business should the asset fail to perform operationally in the facility. The model can be applied to all high-value complex assets with parts which are not currently surveyable under the current lifecycle-modelling process.
- The study makes an important contribution to knowledge through the statistical procedures employed, from which an appropriate outcome can be obtained. This is a key contribution and was discussed during the literature review. The current practises used for asset-replacement forecasting are under much scrutiny. This study utilises existing data currently lying dormant in isolated silos across the UK and merges the data to create failure distributions based on real replacements to probabilistically model the future lifecycle costs of AHUs.
- The use of Rhino5 and Grasshopper as a means to represent lifecycle-replacement models is currently an unused tool in the industry. Primarily used in the field of

interactive architecture, the tool was first used during the research masters (MRes) in conjunction with artificial intelligence algorithms to control lux levels in internal spaces (see Appendix 24 – paper).

- The lifecycle model is dynamic, and the various Options (1-4), indices, part costs, etc, can be updated parametrically to take new data or risk-appetite levels into account. The geometrical model will automatically update the results of any changes to the lifecycle model in real-time.

The model overcomes the current industry-wide disadvantages of existing models because it probabilistically deals with inputs and outputs (while retaining the surveying function so as not to compete with the current resource requirements of a survey), and puts all stakeholders in a position to do their jobs with greater efficiency and understanding than through using the outputs of previous models.

8.3 Limitations of the Research

The model is an improvement on current life cycle modelling approaches and informational output streams seen in the PFI industry to date, but is still far from perfect. The key limitations of the research are presented below. They consist of a combination of technical and philosophical shortcomings which arose from the research process as well as from the time spent in facilities and offices and from understanding the context to which the work applies.

8.3.1 The Link between Strategy and Operations

An increased level of understanding between the survey team members means a greater level of cooperation and awareness of how one team member affects the other. By surveying the equipment together, as a team, both surveyors were able to debate and put forward their reasons for categorising an asset's risk level, from a top-down (HCP) and bottom-up (Skanska) method.

8.3.2 Equipment Start-Dates

The model proposed that the commissioning date of each AHU be used. Quite often, this data was identical to that of the other AHUs within a phase, suggesting that all AHUs had been installed and commissioned on the same day. Rather than phase-level start dates, individual start dates would make the model more accurate in terms of future prediction. The likelihood of this data having been collected is not high. However, it could be a data point for storing in BIM models in future projects.

8.3.3 Asset Runtimes

The evaluation of service life takes the period during which the asset is intended to be used for its function or business purpose into account. Frequently, this period will dictate the period of analysis of the WLCs and may dictate the design life for major assets and components (CIBSE, 2008). The runtime of each AHU was the key damage mechanism which indicated a common thread between the assets. The runtime of each asset was deemed to be 22.9 hours per day, based on BMS data collected from HCP1. The reality is that many hospitals do not have this AHU-runtime data readily available because there is either no BMS or the BMS installed is so old that visualising or outputting the runtime settings for assets is not achievable. The research does however concede that not all the assets are run for 22.9 hours per day; collecting the runtime data for the AHUs which required replacement parts in the first place would actually be an improvement to the model.

8.3.4 Comparability of Part Failure Data

The research scope focused on healthcare facilities for the data collection process rather than any other type of facility because it was deemed that healthcare assets would experience a higher ratio of use and incur a higher level of contractual penalties for failure. However, the sheer size and value of HCP1 in comparison to the other healthcare facilities in the HCP portfolio may mean that the data collected may not be directly comparable to its counterparts because the demand on the equipment (as a result of the hospital treating more patients and experiencing different levels of use) may differ.

8.3.5 Distributions Based on Part Sizing

The range of motor sizes across the HCP portfolio ranges from 0.55kw to 30kw. In future, a distribution for a motor could be based on its part characteristics rather than simply the part itself. This could also be said for differing sizes in coils, fans, humidifiers, and etcetera.

8.3.6 Motor Runtimes

According to the data collected for the 48 motor failures, the runtimes were assumed to be 50/50. The actual runtimes of the motors are not however known because some will be based on an *n* system and some on an *n+1* system. N+1 systems tend to indicate a more critical part (hence the natural halving of the motor runtimes in the model); however, the truth remains that a motor which is part of an n+1 system should be run for the same amount of time as its counterpart but this all depends on the level of professionalism of the HFM maintenance team. Research conducted in this area has shown that the runtimes for such parts are not even and this complicates the future replacement prediction methodology still further.

8.3.7 Overheads

Overhead margins on the work were not included in the model because only a fragment of the invoice data contained any overhead information.

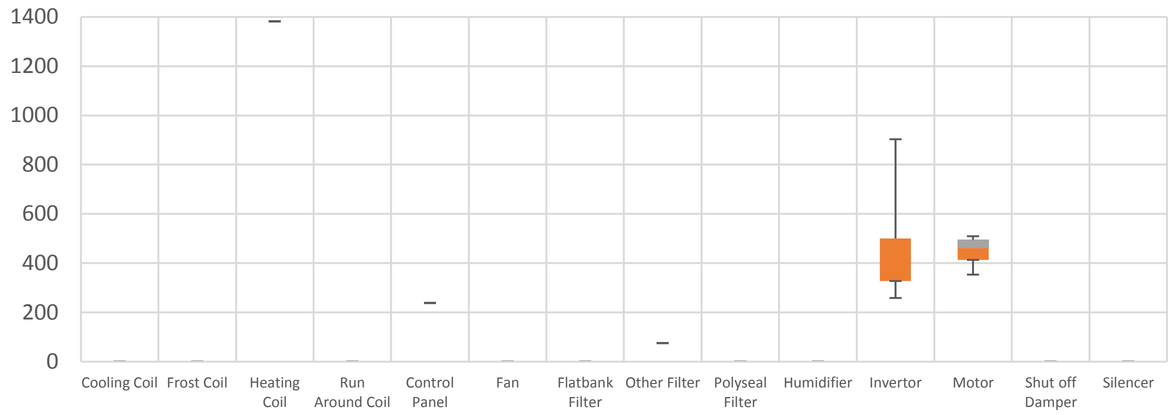


Figure 80: Overheads graph

Table 40: Overheads statistics

	Cooling Coil	Frost Coil	Heating Coil	Run Around Coil	Control Panel	Fan	Flatbank Filter	Other Filter	Polyseal Filter	Humidifier	Invertor	Motor	Shut-off Damper	Silencer
Min	n/a	n/a	£1381	n/a	£238	n/a	n/a	£75	n/a	n/a	£259	£353	n/a	n/a
Q1	n/a	n/a	£1381	n/a	£238	n/a	n/a	£75	n/a	n/a	£327	£412	n/a	n/a
Median	n/a	n/a	£1381	n/a	£238	n/a	n/a	£75	n/a	n/a	£500	£461	n/a	n/a
Q3	n/a	n/a	£1381	n/a	£238	n/a	n/a	£75	n/a	n/a	£500	£494	n/a	n/a
Max	n/a	n/a	£1381	n/a	£238	n/a	n/a	£75	n/a	n/a	£902	£509	n/a	n/a

The overheads attributable to part replacement were seldom disclosed in a manner useful for analysis. This is due to the different ways in which costing and charging for parts currently happens on site. While some data was collected for the expected overheads and labour (attributable to motor and inverter replacements), a notional 20% has been factored into the model, mirroring HCP's current allowance for overhead and labour costs. That means that a fairer comparison between Options C and 1, 2, 3 and 4 can be made.

8.3.8 The Removal of Hospitals from the Data Collection Exercise

Certain contracts have no control over the lifecycle fund. The risk is with the HFM team and, as such, no invoices are issued to the SPV and the data becomes commercially sensitive to HCP from an HFM standpoint. The reason for this commercial sensitivity is because relaying this data would allow HCP and the SPV to be able to calculate the profit margin of the HFM subcontractor more accurately. Where this actually occurred, the data was unable to be collected.

8.3.9 Distribution Fitting and Thresholds

Anderson-Darling testing and probability plotting provided a unique view on unique part data. A decision was taken that those part replacements with an r2 value of >0.85 and AD value of >0.005 accepted the null hypothesis that the data formed the beginning of a normal distribution. Much like establishing the shape parameter of the Weibull distribution, there is no hard and fast method of delineating between what can be deemed a 'good fit' and what cannot. This is particularly true with a limited data set. The r2 value of 0.91 appears to be a good fit in the case of the humidifier profile, however this distribution may have been better modelled using a Weibull function rather than a normal distribution.

8.3.10 Distinguishing between Internally and Externally-Mounted AHUs

The risk survey exposed the fact that there are significant environmental differences between an internally and externally mounted AHU. There is an argument which suggests the AHU-failure data should be further delineated into 'externally-mounted parts' and 'internally-mounted parts' because of the differences in such exposure levels. This is further supported by CIBSE's generic lifetime guidance (on an AHU level) of 25 years for an internally-mounted AHU and only 20 years for an externally-mounted counterpart.

8.3.11 Risk Modelling on a Part Level

Some components may be more critical than others in terms of the overall risk to the business (CIBSE, 2008). The risk survey was carried out on an AHU level. The reason for this was primarily to differentiate between the assets, but it was also due to the constant use of the AHUs, and their criticality as a system meant that internal inspection was not possible. However, there is an argument to suggest that some parts such as silencers may not cause the complete failure of an asset (rather just an increase in noise pollution) and therefore there should be some additional weighting on part levels to account for the different impacts caused by part failure. Similar works have suggested systematic component evaluations prior to deciding on whether to extend a unit's service life or not (Presnak and Yee, 2014).

8.3.12 Data Quality

The BSI presented a method on the process of selecting RSL data and this was adhered to when selecting the best data to input into the model. However, the historical data which *is* available is not likely to be available in a good format across all facilities, often containing unnecessary information or being hard copy only. The stark reality involved physically travelling across the country collecting hard-copy invoice data. In future, if some form of cloud-linked repository could be set up it would make the process of compiling a comprehensive failure database much simpler.

8.4 Future Developments

Research undertaken during the course of this thesis has highlighted the limitations of the method above. There still remains considerable scope for further development in the field of risk-based lifecycle modelling and geometrical visualisation in the PFI asset-management industry. Some of the key areas of further development are discussed below.

8.4.1 Responsibility Matrix and Maintenance Cap

One of the assumptions within the model was that if no failure had been recorded, the given part was not deemed to be included within the scope of the SPV's financial planning responsibility. An area of improvement for research in the future could be investigating the contractual liabilities versus the reality of what actually happens within operational lifecycle works on site. Does more or less lifecycle work actually occur outside the SPV's area of responsibility? This is pertinent with regard to lower cost items such as flat-bank filters (none of which were recorded as failing during data collection). These parts and other similar ones could be replaced on a one-by-one basis, falling directly under maintenance, or could be batch ordered, bringing the cost into the thousands (above the maintenance cap and into the SPV lifecycle budget). This aspect of lifecycle modelling is further complicated by differing contracts for differing SPVs, many of which contain no responsibility matrix at all. Bearing this in mind, a better approach for collecting failure data could be devised through understanding that PFI contracts are different and so is the way their data is collected and stored. Because the research was conducted from a head office complex, with site visits to the facility, the actual day-to-day running of a hospital was never experienced.

8.4.2 Geometrical Data-Import Barriers

Incomplete geometry was apparent when the BIM model was imported. For example, the casing on AHU25S was not complete and fans/motors had to be included on the basis of the AHU drawings from site. This is a data-import issue, and one which could have been avoided had the Navisworks file been available in something other than a 'read only' format. In the case of AHU35AE, additional components were found in the model, which, on physical inspection, should not have been there.

8.4.3 Geometrical Level of Detail

Level of Detail could be considered a drawback within the research. The level of detail with which BIM models are built is designed with construction in mind. 'Parts of parts' (such as bearings on motors) were out of the research scope because the geometrical model did not present such a level of detail (and neither did the AHU drawings!). Future models could include such detail on critical units such as the AHUs and thus the lifecycle prediction models produced would increase in accuracy. Currently there is no demand nor any economic model in the industry which might demonstrate the benefits of such an undertaking. Until models become more detailed, the operational planning and confidence in decision-making ability will be restricted.

8.4.4 Technology as a Factor in Distribution Forecasts

A consideration should be made regarding technology as a factor in the future replacement of assets and parts. There is an argument to say that as a progressive race, we will get better at building things to last. Ergo, a part replacement in 2015 may be slightly earlier than in 2050 based on the assumption that new materials and technology will be available to produce more durable components. On the other hand, there is an argument to say that the more technology we embed in our buildings, the more room for error (and thus failure) we actually create.

8.4.5 Indexation

PALM mirrored an RPI rate of 2.5% to make Options 1, 2, 3 and 4 comparable to Option C. A more granular level of indexation, as opposed to a blanket indexation, may increase the accuracy of the model looking ahead. This issue is linked to data collection in that until the data on part prices can be viewed graphically over time, the indexation attributable on a part basis still remains out of reach

8.4.6 Asset Management Level of Detail

The question still remains as to how much data is too much data on which we can base a decision. This is partly due to time and the value of an exercise versus how much it saves/gains the business. But it is primarily down to two opposite ends of businesses being connected to the same model. Strategically, decisions must be made on top-level information such as how much should be budgeted in each year, however the physical replacements of these parts is a reality and the two business levels do not interlink easily. A discussion about where to 'stop' life cycling from an economic standpoint is needed.

8.4.7 Artificial Intelligence as a Cost-Prediction Method

Chapter 3 discussed the application of artificial neural networks as a method of cost prediction. While cost prediction was not at the forefront of the research, Figures 81 to 85 illustrate the relationships between various AHU characteristics for the 113 AHUs at HCP1. There are clear correlations between some of the geometrical proportions of the assets as well as their technical capabilities. The most positive correlation to be found was that between the front surface area of the AHU and the air volume. The *r2* coefficient was found to be above 0.95, making this a particular input-variable candidate for artificial intelligent algorithmic design.

The potential for improving cost prediction through artificial intelligence is significant. Clear input values based on AHU and component-unique features could form the basis for cost predictions in the future. This could be done through collecting a cost-data sample of a part along with the characteristics of the AHU to which it belongs. The possibility of carrying out this exercise would mean the collection of thousands of data points on which to train the model, before testing. The output would be the cost of a part based on its parent asset's individuality (i.e., the AHU). As HCP and other non-PFI assets begin to deteriorate over the course of time, this data will form an invaluable database for cost prediction of AHUs in new hospitals in the future.

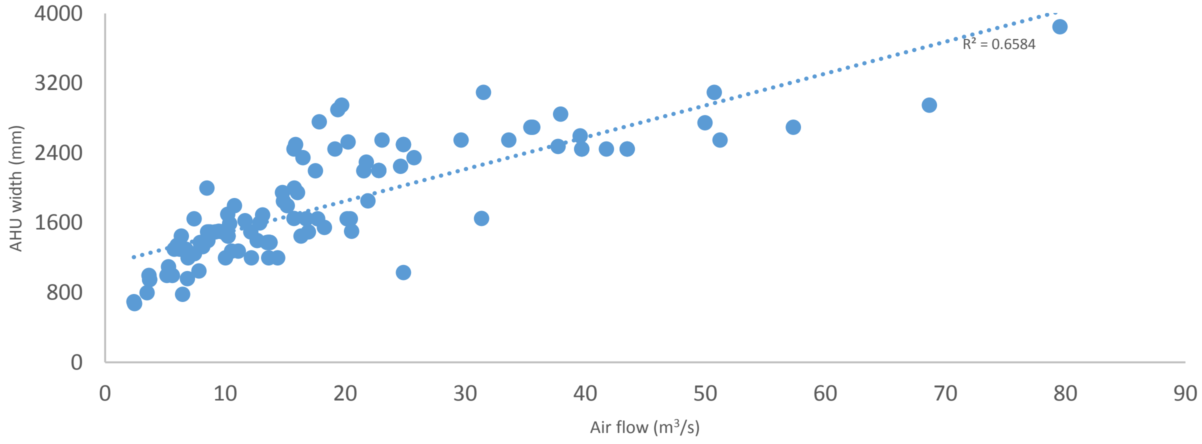


Figure 81: Relationship between air flow and AHU width

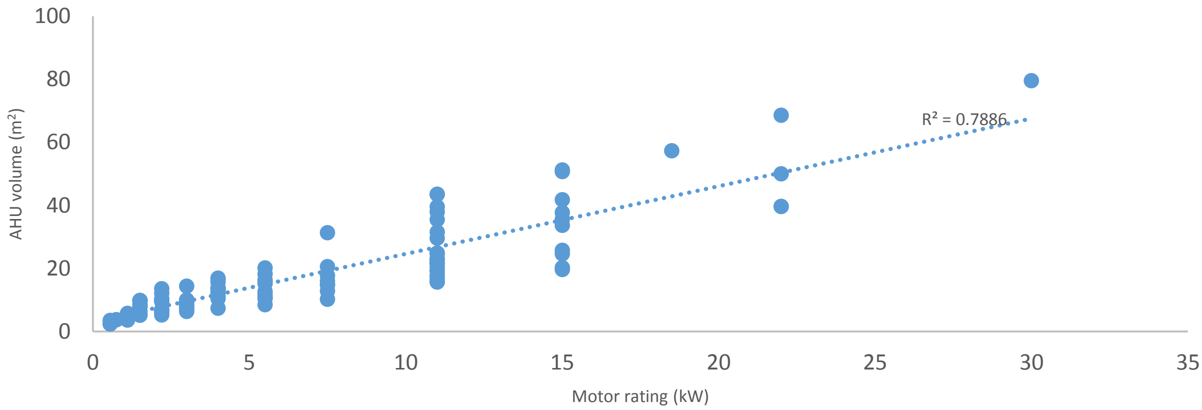


Figure 82: Relationship between AHU volume and motor rating

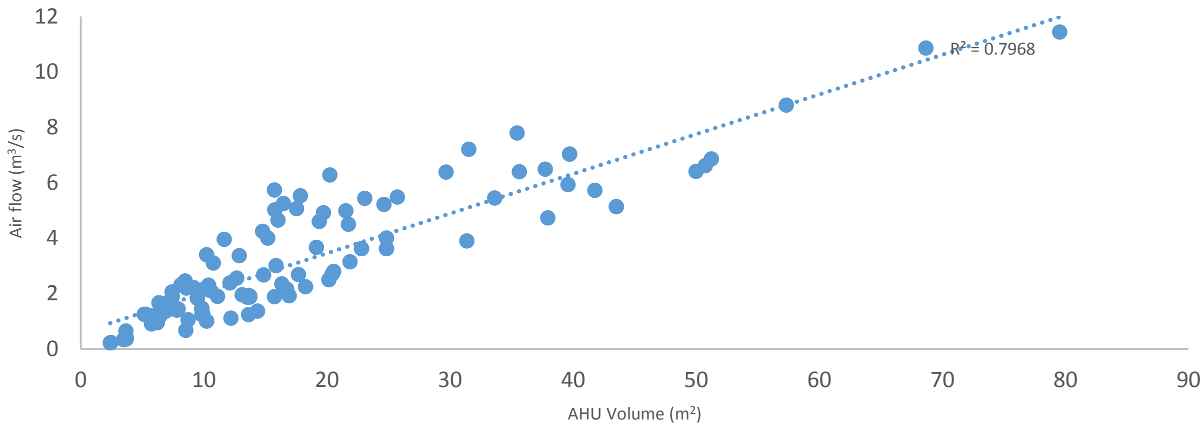


Figure 83: Relationship between air flow and AHU volume

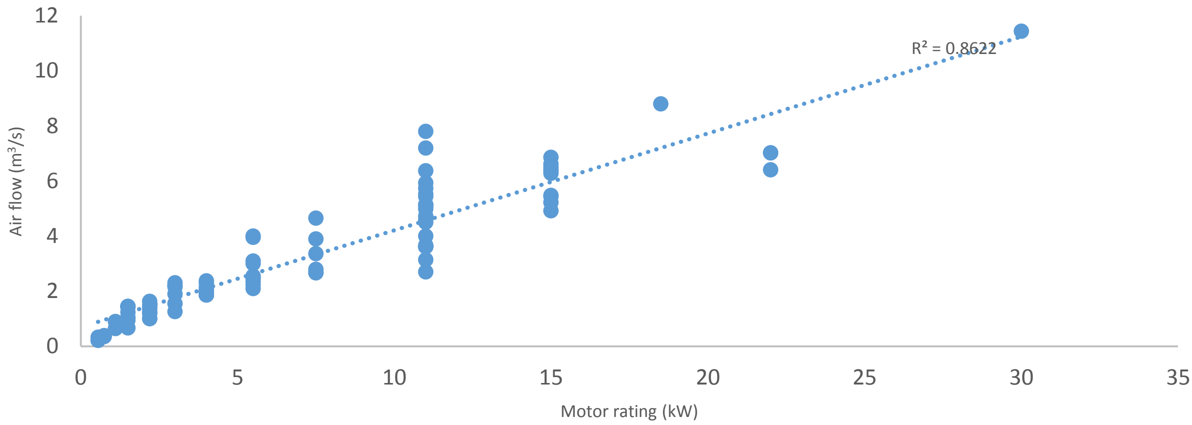


Figure 84: Relationship between air flow and motor rating

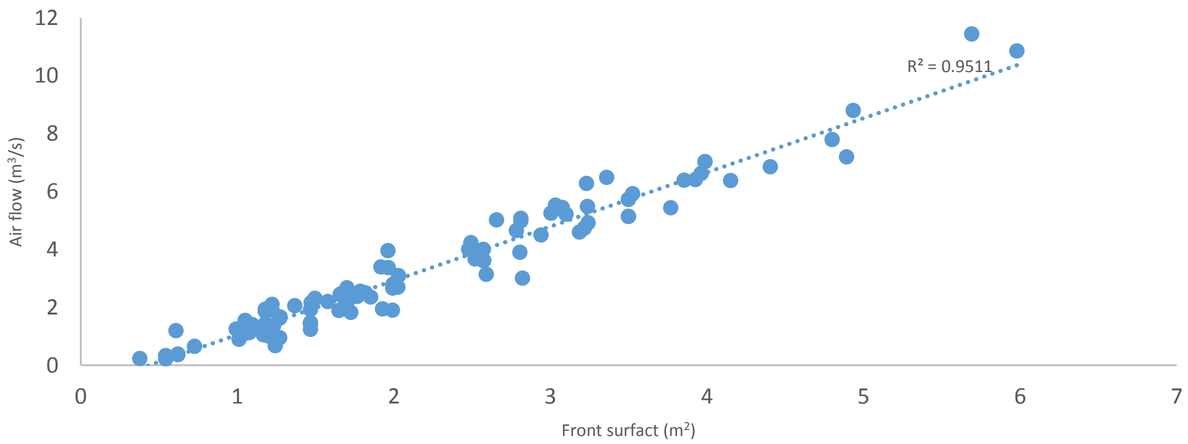


Figure 85: Relationship between air flow and front surface

8.4.8 Immersive Visualisation and Virtual Reality

Throughout the research, the researcher has been part of the UCL virtual reality group, which explores the nuances of how to import various data structures into computer-aided virtual reality (CAVE) software platforms. Unity is renowned for its ability to be able to render upwards of 50,000 vertices with multiple meshes. The PALM geometry has a mesh count in the hundreds of thousands and a vertices count in the millions. Future research could focus on how best to visualise and render the geometry for 3D viewing using Oculus Rift or Ogre 3D. The benefits of decision-makers theoretically being able to 'walk' around and view their assets from a board room anywhere in the world is an exciting prospect. A business case as to the benefits of such a progression in visual modelling is not difficult to make.

8.4.9 The Risk Variable Weightings

Chapter 5 discussed the engineering risk and paymech risk as forming an equal ratio in terms of lifecycle-replacement suggestion. In future, it may be worth querying whether one aspect of risk is more important than another and adjust the weightings accordingly.

8.5 Summary

While the research has yielded some vast improvements on the way life cycle profiles are built a number of limitations to the research have been identified:

- The link between strategy and operations still remains untied
- Equipment start dates have no agreed 'beginning'
- Asset runtimes have been estimated using a mean where data was not available
- Part failure data comparability only becomes useful with a larger number of assets
- Distributions based on part sizing have been ignored due to a lack of data
- Overhead costs are largely unrecorded across PFI healthcare projects
- Hospitals in the data mining exercise (HCP 2-18) were reduced to 6 because of various access-to-data hurdles
- Internal and externally mounted AHUs should be categorised with a greater distinction

These limitations and the lack of validation do not affect the usefulness of the results, however they do demonstrate that life cycle costing and visual modelling remains some way from becoming a regulated industry. While data remains either safeguarded or uncollected, the true accuracy in predicting future life cycle replacement costs will remain understated. The study reviewed AHUs in a healthcare setting; however this is unlikely to impact results should the AHUs have been data recorded from difference sectors. The asset runtimes may differ from industry to industry dependant on how 'critical' a nature the facility provides. This prompts the following recommended future developments:

- Work on the future importability of geometry from BIM packages into parametric modelling packages will produce a greater visual output.
- Improving the level of detail within BIM models will ultimately yield more accurate physical asset life cycle models.
- Considering future technological advances will improve model forecasting
- Artificial intelligence can be used as a powerful tool in predicting failure but it dependant on data accessibility improvements for researchers.
- Immersive visualisation of geometrical life cycle models could revolutionise how decision-making is made.

Perhaps the most important avenue of enquiry going forwards would be that of artificial intelligent cost prediction. Predicated on good data collection this type of complex modelling has the potential to revolutionise the performance of life cycle costing as a client offering. The upshots of such an improvement would be a greater clarity of future costs on a facility level and greater economic stability on a national level.

Chapter 9. Concluding Remarks

9.1 Revisiting the Research Aim and Objectives

The aim of the research was to:

'To develop a data-driven risk-based lifecycle replacement funding model and visualisation tool to improve the decision-making of mechanical assets in the PFI Healthcare sector.'

The BSI stated that few models have been produced which simply and accurately depict replacement life whilst maintaining an element of practicable implementation and translatability for other works (2008). PALM is one which removes the impractical implementation suggestions (based on current models operating under the guise of 'strategy') and replaces them with a profile which provides operational realism. This chapter will conclude by bringing the research dialogue back to the first chapter, which set out the research questions and objectives. The research objectives set out in Chapter 1 were:

- To create a model building approach based on a detailed understanding of the PFI business model and context.
- To develop a model to improve using the necessary factors to achieve the solution.
- To build a model that can be translated and expanded to other projects in future.
- To qualitatively collect and analyse feedback from stakeholders in the position of approving lifecycle works.

9.2 Current Life-Cycling and the Life-Cycling Approach for Air-Handling Units

Current data-collection approaches place the onus on the surveyor to successfully predict the life of an asset through a condition-led survey. The condition survey sets out to 'classify' the condition of an asset through grading levels (A to X – Table 1) and the condition definitions are applied across all assets from air-handling units to towel dispensers. The outcome of this survey is a lifetime prediction for the AHU. Often, for professional indemnity insurance reasons, the surveyor will recommend a life consistent with that of CIBSE best-practice guidance. This is done on an AHU level. CIBSE recommends an expected lifetime of 25 years for an internally mounted AHU and 20 years for an externally mounted AHU.

Overall, such an approach is acceptable for low-cost assets or those aspects of lifecycle which are 'straight forward' (such as cyclic-painting regimes). However, such approaches to lifecycle modelling of complex assets are inferior and persist in business for the following reasons:

- *Physical Inaccessibility* – the AHUs are (comparatively speaking) high-risk assets and are in use at least 16 hours per day. The majority of AHUs at HCP1 are used 24 hours per day and that makes physical inspection on a component level almost impossible.

- *Data Inaccessibility* – due to the SAM-survey team not being located on site, obtaining information such as the BIM model or AHU drawings was a task which had not been undertaken since the research took place.
- *Unfamiliarity with BIM* – at best, very few MSPs utilise BIM models. Prior to the research project, HCP did not utilise the BIM model for operational purposes. This creates unfamiliarity with BIM and therefore a barrier for understanding the AHU components through the geometrical model.
- *Lack of business case* – as yet, there is no business case for demonstrating the economic benefits of changing the approach which HCP currently employs for air-handling unit lifecycle.
- *Time constraints* – HCP is one of 37 projects in the HCP portfolio, and the AHUs account for less than 10% of the current lifecycle budget. Accurate time evaluations for asset-level surveying of air-handling units means HCP will be confident it can deliver to clients on schedule. A change from asset to component level could affect their ability to deliver lifecycle models on time.

9.3 Considering Lifecycle Costs

BSI defined Lifecycle Costing as “the costs associated with acquiring, using, caring for and disposing of physical assets”. ISO 15686:2008 defines lifecycle costs as *including the construction, operation, maintenance and end-of-life phase*. Within the boundaries of this definition, the costs considered in the strategic management of AHUs within a PFI contract fall strictly within the maintenance phase because of the finite window of responsibility the MSP/SPV is required to deliver. Chapter 3 looked at which costs within the commonly used term ‘lifecycle’ should be adopted into the more specific PFI PALM:

- Capital costs – one-off expenditure relating to a facility – *excluded*
- Operational costs – a broad term, but covered during section 3.2.3 -*included*
- Acquisition costs – the cost included in acquiring an asset – *excluded*
- Nominal, real and discounted costs – *included*
- Disposal costs – *excluded*
- End-of-life costs – *excluded*

Lair and Chevalier (2002) presented a way of varying the targeted costs to allow for fiscal differences in the resultant lifecycle profile depending on the decision-maker’s appetite level. This was adopted and inspired the 4-option choice system within PALM. PALM used a mean-compound interest rate of 2.5% because it was deemed reasonable by the HCP commercial team and made the outputs directly comparable to Option C. The costs per part were collected during the data-collection exercise and, although an artificial neural network had been originally planned to forecast the costs (due to a lack of data points necessary for training), the mean cost was taken. The mean costs for the parts can be found in Table 35. The only part which had no cost recorded was the silencer and so Allaway Acoustics was contacted which recommended a part cost of £235 (see Appendix 25). On-costs for parts were barely recorded which meant that a blanket value of 20% was applied on top of the mean-part costs. This 20% figure was used as it was the value currently prescribed by HCP when modelling on an asset level and therefore ensured comparability between option C and the four PALM options presented.

9.4 Techniques Available for Modelling Lifecycle Differently

The current technique for modelling lifecycle is based on the condition survey which translates directly into a FCI, or *facility condition scale* (shown in Table 4). The results of the current model approach form the basis of *how we invest* capital, as illustrated in ISO 55000's asset reinvestment logic diagram. The *Building Valuation Model, Lifecycle Actuarial Model* and *Mathematical Parametric Model* between them cover the approaches which are currently used in industry. These models are, however, flawed in so far as they base their funding profiles on the original condition survey data, which is high (asset) level, generic and often compromised by personal indemnity insurance issues.

New, engineering-based techniques that are currently used mainly in the manufacturing, medical or material engineering industries have been considered. These include:

- Regression Analysis
- Auto-Regressive Moving Averages (ARMA)
- Artificial Intelligence
- Monte Carlo simulation
- Probability Distributions

The Monte Carlo simulation and Probability Distributions were adopted for the study because the stochastic nature of the Monte Carlo simulation could be used to plug the gaps in data where not all the information was available.

The survey process highlighted some faults with the AHUs and these were noted during the study. Including this process avoids a paradigm shift and makes PALM one which goes with (rather than against) the grain of the business model currently employed within PFI asset management.

9.5 Understanding Risk

Woodhouse's diagram (Figure 21) shows example decision options when faced with ageing assets. Such decisions can be made more straightforward by assessing the unique risk factor of the asset in question. CIBSE splits risk into 4 categories: *business*, *design and installation*, *operation and maintenance* and *disposal*. Conachey's (2008) study used risk to logically reallocate resources so that the highest risk received the most attention in terms of maintenance. This, among other studies (such as Ujjwal's research into corrosion as the damage mechanism (2012) by which the lifetime can be estimated), proves that the ways of modelling risk are virtually boundless. This could partly be due to the many definitions of the term and the varying contexts in which almost every business and sector operates. The risk-based approach meant drawing the conclusion that the problem at hand was both engineering- and contractually-based. Put simply, if an AHU serves an area which would have a negligible financial impact should the unit fail, there will be a low incentive to fix that part. This is typical of fiscally-based logic and is unlikely to change any time soon, hence why the contractual risk and engineering risk factors were as important to the process of informing lifecycle replacement. The model accepts that the key components of risk are probability and time. The engineering- and financial-risk combination weaves neatly into the cumulative-density functions by producing unique replacement times which depend on the seven factor categories (from the survey), the financial implications of failure (paymech risk), part runtime at HCP (22.9 hours) and component-level failure data. The theory of how this works can be seen in Figure 43 and the resulting impact of such an understanding of risk is a lower, more realistic lifecycle model and profile.

9.6 The Impact of Component-Level Replacement Models

Table 2 in Chapter 1 sought to explain the current costs associated with the Lifecycle Costing of AHUs at HCP1 through common metrics used in the industry. The resulting costs arise because of the *way* the assets are surveyed, costed and modelled. The PALM theory is highlighted best in Figure 36. The metric of the proposed options can be seen in Table 36 (key statistics across all options)

The PALM lifecycle-modelling approach has demonstrated a minimum saving of over £1m on the current lifecycle budget planned by HCP during the concession period (ending March 2048). The differences are displayed below:

Table 41: Financial budget differences according to options

Option Scenarios					
	Option 1 - Recommended	Option 2 - Conservative	Option 3 - Balanced	Option 4 – Optimistic	Option C – Current
Lifecycle Expenditure (Date - Mar 2048)	£ 3,889,325.00	£ 4,549,735.00	£ 4,316,696.00	£ 3,447,945.00	£6,045,470
Difference (£)	-£2,156,145	-£1,495,735	-£1,728,774	-£2,597,525	n/a
Difference (%)	-35.6%	-24.7%	-28.6%	-42.9%	n/a

9.7 BIM Geometry as a Visual Aid for Decision-Makers

Three members of the HCP Board were interviewed following a presentation at the December 2015 HCP Board meeting. As discussed in the previous chapter, the tool was well received and the members agreed that their knowledge, and therefore decision-making abilities, regarding the AHUs had increased as a result. While PALM displays areas of improvement, the tool demonstrates that visual-support tools can be used to aid in stakeholder understanding and decision-making ability. Some of the key outputs from the thematic analysis of results showed that:

- The model can improve understanding – particularly from a non-technical point of view.
- Understanding is not confined to the HCP Board but to external stakeholders as well.
- Decision-making can be improved but it is important not to overstate the reliance on hard data.
- Board members feel more confident in the lifecycle prediction when they can physically see and pair together the replacement-schedule figures and model.
- Senior decision-makers are becoming more aware of the operational implications of a lifecycle model through seeing part-replacement strategies presented visually.
- The model can be adapted in future for a different but equally critical asset-management business area, such as functional obsolescence.
- The demonstration of a tool like this has rarely been seen before and, as such, it can provide HCP with a competitive edge in the PFI marketplace.
- The way ahead for lifecycle modelling could rely on such modelling approaches in the future.
- The model can be integrated into HCP business propositions for new and existing clients in PFI and beyond.

Direct accessibility to business leaders proved invaluable in terms of gaining feedback and improvements on the tool and is a key advantage in industry-led research.

9.8 Summary

Since its inception in the early 1990s, the need for a better understanding of lifecycle modelling in the PFI industry has been something of an ‘elephant in the room’ amongst asset managers, investment directors, other decision-makers and stakeholders, who are all directly affected by the resulting budget and fiscal decisions. The current survey-led method uses no historical data, irrespective of the fact that the notion of a lifecycle would predict that more and more data will be produced on the performance of parts as the contracts age. PALM was applied to what is perhaps the most complex physical asset in perhaps one of the most complex facility management environments in which to explore lifecycle modelling and visualisation on a component level of detail previously unseen in industry.

As things currently stand, the significant income streams and vague budgeting plans for lifecycle modelling mean this area is ripe for research opportunities, with clear financial benefits on offer as a result of better replacement life-prediction of components. Adopting PALM techniques will provide a more wholesome approach than what is currently on offer in the PFI AM industry through placing a greater emphasis on the interlinking of the survey process, contract between MSP and client and empirical data on the parts of assets. This allows decision-makers on the strategic level and lifecycle practitioners on the operational level to be able to make forecasts of lifecycle costs with a greater level of accuracy and retrospective accountability. While the tool has its limitations, one of the fundamental successes of the research has been that all stakeholders and players feel they have something to comment on and discuss whether working in the Board room *or* plant-room. This is because the data is *clear, transparent and understandable*, a far cry from the output provided by the current methods, to date.

In the future such a tool will facilitate decision-makers' abilities to manipulate budget levels to ensure leaner and operationally more realistic facility management practices, based on evaluating the risk of complex, often un-surveyable assets which for all intents and purposes, the industry currently views as largely identical.

References

1. Adan. A, Xiong. X, Akinci. B and Huber. D. (2011). Automatic creation of semantically rich 3D building models fromlaser scanner data, *Proceedings of the International Symposium on Automation and Robotics in Construction (ISARC).*
2. Ahadzi, M. and Bowles, G. (2004). Public-private partner-ships and contract negotiations: an empirical study. *Construction Management and Economics*, 22(9), 967–78.
3. Abmayr. T, Hartl. F, Reinkoster. M and Frohlich. C. (2005). Terrestrial laser scanning applications in cultural heritage conservation and civil engineering. *Proceedings of the ISPRS Working Group V/4 Workshop 3D-ARCH 2005, Virtual Reconstruction and Visualization of Complex Architectures.* International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Mestre-Venice.
4. Akcamete. A, Akinci. B and Garrett. J. H. (2010). Potential utilization of building information models for planning maintenance activities. *Proceedings of the International Conference on Computing in Civil and Building Engineering*. Nottingham University Press.
5. Akintoye. A, Hardcastle. C, Beck. M, Chinyio. E and Asenova. D. (2003). Achieving best value in private finance initiative project procurement. *Construction Management and Economics.* 21(5), 461–70.
6. Al-Hajj. A and Homer. M. W. (1998). Modelling the running costs of buildings. *Construction Management and Economics*. Volume 16 Number 5.
7. Ali. N, Sun. M, Aouad. G, Mazlan R.D, Mustapa. F.D. (2006). Understanding the business process of reactive maintenance projects. *International Conference on Construction Industr*y, 21–25 June, 2006, Padang, Sumatera Barat Indonesia.
8. Amekudzi. A.A, McNeil. S. (2008). Infrastructure Reporting and Asset Management: Best Practices and Opportunities. ASCE Publications.
9. Arayici. Y. (2008). Towards building information modelling for existing structures, *Struct. Surv.* 26. 210–222.
10. Armesto. J, Lubowiecka. I, Ordóñez F. and Rial. F. (2009). FEMmodeling of structures based on close range digital photogrammetry, *Autom. Constr*. 18. 559–569.
11. Asri. Y. M, Azrulhisham. E. A, Dzuraidah. A. W, Shahrir. A, Shahrum. A and Azami. Z. (2011). Fatigue Life Reliability prediction of a stub axle using Monte Carlo simulation, 12(5), 713–719. doi:10.1007/s12239
12. Audit Commission. (2003). PFI in Schools, London: Audit Commission.
13. Atrium. (2014). Atrium EAM system and BIM Integration Overview, 1–19. www.atriumsoft.com/. Accessed May 2015.
14. Ball. R and King. D. (2006) The private finance initiative in local government. *Economic Affairs*, 26(1), 36–41.
15. Ball, R., Heafey, M., & King, D. (2007). The Private Finance Initiative in the UK. Public Management Review, 9(2), 289–310. doi:10.1080/14719030701340507
16. Barrett,P., Baldry. D., (2003) Facilities Management: Towards Best Practice. 2nd, Blackwell Science, Oxford.
17. Bazjanac. V, (2008) Virtual building environments (VBE)—applying informationmodelling to buildings, in: A. Dikbas, R. Scherer (Eds.), eWork and eBusiness in Architecture Engineering and Construction, Taylor and Francis, London, UK, 2008.
18. Becerik-Gerber. B., F. Jazizadeh, N. Li, G. Calis, (2012) Application areas and data require-ments for BIM-enabled facilities management, J. Constr. Eng. Manag. 138. 431–442
19. Beraldin, J.A. (2004). Integration of laser scanning and close-range photogrammetry – the last decade and beyond International Society for Photogrammetry and Remote Sensing (ISPRS) Congress, Commission VII, International Society for Photogrammetry and Remote Sensing (ISPRS), Istanbul.

20. Barlow, James; Roehrich, Jens K.; Wright, Steve (2010). De facto privatisation or a renewed role for the EU? Paying for Europe's healthcare infrastructure in a recession. Journal of the Royal Society of Medicine 103: 51–55. doi:10.1258/jrsm.2009.090296
21. Bowden, R. J., & Zhu, J. (2010). Multi-scale variation, path risk and long-term portfolio management. Quantitative Finance, 10(7), 783–796. doi:10.1080/14697680903460119
22. Box, G.E.P. and Jenkins, G.M. (1970) Time series analysis, forecasting and control, San Francisco, Holden Day.
23. Broadbent, J., Gill, J. and Laughlin, R. (2003) Evaluating the Private Finance Initiative in the National Health Service in the UK, Audibility and Accountability Journal 16: 3 pp422 – 45
24. Brown, R. J. (1979). A New Marketing Tool : Lifecycle Costing, 13, 109–113.
25. BSI. (2000). Buildings and constructed assets -Service life planning -Part 1 : General principles.
26. BSI. (2008). Buildings and constructed assets — Service-life planning Part 8: Reference Service Life and Service-life estimation.
27. BSI. (2011). Buildings and constructed assets — Service life planning Part 1 : General principles and framework.
28. BSI. (2014). Building Construction — Service Life Planning Part 4 : Service Life Planning using Building Information Modelling.
29. BSI ISO 31000. (2010). ISO 31000 BSI Standards Publication Risk management Risk assessment techniques.
30. Burns, P., Hope, D., Roorda, J., 1999. Managing infrastructure for the next generation. Automation in Construction 8, 689–703.
31. Cabinet Office (2013). Government Property Unit The Government Soft Landings Policy – September 2012.
32. Cerovsek. T., (2011). A review and outlook for a "Building Information Model (BIM)":a multi-standpoint framework for technological development, Adv. Eng. Inform. 25. 224–244.
33. CIBSE. (2008). Guide M: Maintenance engineering and management -A guide for designers, maintainers, building owners and operators, and facilities managers. ISBN 978-1-903287-93-4
34. Carrillo, P., Robinson, H., Foale, P., Anumba, C. and Bou-chalaghem, D. (2008) Participation, barriers, and oppor-tunities in PFI: the United Kingdom experience. Journal of Management in Engineering, 24(3), 138–45.
35. Chatfield, C. (1978) The Holt-Winters forecasting procedure, Applied Statistics, Vol 27, pp 264-279
36. Clayton, M.J., Johnson, R.E., and Song, Y., (1999). Operations Documents: Addressing the Information Needs of Facility Managers. Durability of Building Materials and Components, 8 (4), 2441-2451.
37. Conachey, R., Serratella, C., & Wang, G. (2008). Risk-based strategies for the next generation of maintenance and inspection programs. WMU Journal of Maritime Affairs, 7(1), 151–173. Retrieved from http://link.springer.com/article/10.1007/BF03195129
38. Costin, Pradhananga, Teizer (2012) Leveraging passive RFID technology for construction resource, field mobility and status monitoring in a high-rise renovation project. Autom. Constr. 24. 1–15
39. Dalton, B., & Parfitt, M. (2013). Immersive Visualization of Building Information Models, (6), 1–20.
40. Daskalova, S., (2008). A Reserch Focused on Possible Applications of Second Life. University of Applied Sciences. School of Communication and Media. Major International Communication: For the University Medical Center Goningen-Advisory Investigative Reporthanze.
41. Davies, H., & Wyatt, D. (2004). Appropriate use of the ISO 15686-1 factor method for durability and service life prediction. Building Research & Information, 32(6), 552–553. doi:10.1080/0961321042000291938
42. Design Council. (2015). A study of the design process, 44(0).
43. Dhillon, B.S., 2010. Lifecycle Costing for Engineers. Taylor & Francis, Boca Raton, FL.

44. Dias, J. L., Silva, a., Chai, C., Gaspar, P. L., & de Brito, J. (2013). Neural networks applied to service life prediction of exterior painted surfaces. Building Research & Information, 42(3), 371–380. doi:10.1080/09613218.2013.819551

45. Dickinson. J., A. Pardasani, S. Ahamed, S. Kruithof, (2009) A survey of automation technology for realising as-built models of services, Improving construction and use through integrated design, solutions. 365–381.

46. Donath. D., (2008) Bauaufnahme und Planung im Bestand — Grundlagen, Verfahren, Darstellung, Beispiele, Vieweg+Teubner Verlag,Wiesbaden.

47. Doran. D., Douglas. J., Pratley. R., (2009) Refurbishment and Repair in Construction, CRC Press, Boca Raton.

48. W. East, D. Love, M. Carrasquillo-Mangual, (2012) The COBie Guide (Release 2), buildingSMARTalliance and National Institute of Building Sciences

49. Eastman. T., Sacks. L., (2011). BIM Handbook — a guide to building information modeling for owners, managers, designers, engineers and contractors, Aufl,2, Wiley, Hoboken.

50. M. Economidou, J. Laustsen, P. Ruyssevelt, D. Staniszek, D. Strong, S. Zinetti, (2011) Europe's Buildings Under the Microscope — A Country-by-country Review of the Energy Performance of Buildings, Buildings Performance Institute Europe (BPIE)

51. Ercan, B., & Elias-Ozkan, S. T. (2015). Performance-based parametric design explorations: A method for generating appropriate building components. Design Studies, 38, 33–53. doi:10.1016/j.destud.2015.01.001

52. Flanagan, R and Norman, G (1983), Lifecycle Costing for Construction, RICS, Surveyors Publications

53. Forbes, C.S., & Evans, M. (2011). Statistical distributions. John Wiley & Sons, Inc. Fourth edition

54. Fouchal, F., Hassan, T., & Loveday, L. (2012). Design approach for the integration of services in buildings. Building Services Engineering Research and Technology, 34(3), 333–348. doi:10.1177/0143624412442510

55. Freitag, S., Beer, M., Graf, W., & Kaliske, M. (2009). Lifetime prediction using accelerated test data and neural networks. Computers & Structures, 87(19-20), 1187–1194. doi:10.1016/j.compstruc.2008.12.007

56. Garber, D., Choudhary, R., & Soga, K. (2013). Risk based lifetime costs assessment of a ground source heat pump (GSHP) system design: Methodology and case study. Building and Environment, 60, 66–80. doi:10.1016/j.buildenv.2012.11.011

57. Ghobadian, A., O'Regan, N., Gallear, D. and Viney, H. (eds) (2004) 'PPP, the Instrument for Transforming the Public Services' in A. Ghobadian et al. Public Private Partnerships: Policy and Experience. Basingstoke: Palgrave.

58. Gibbs, G. (2007). Analysing Quantitative Data. Sage Publishing.

59. Golparvar-Fard. M. , J. Bohn, J. Teizer, S. Savarese, F. Pena-Mora (2011) Evaluation of image-based modeling and laser scanning accuracy for emerging automated performance monitoring techniques, Autom. Constr. 20. 1143–1155

60. Grimsey, D., & Lewis, M. K. (2005). Are Public Private Partnerships value for money? Accounting Forum, 29(4), 345–378. doi:10.1016/j.accfor.2005.01.001

61. Gursel. I, S. Sariyildiz, Ö. Akin, R. Stouffs,(2009) Modeling and visualization of lifecycle building performance assessment, Adv. Eng. Inform. 23. 369–417.

62. Haggar (2004) 'An Examination of the Private Finance Initiative – Has the PFI Initiative Assisted in the Investment in our Public Services or Has It Been an Expensive Diversion?' in A. Ghobadian, N. O'Regan, D. Gallear and H. Viney (eds) Public Private Partnerships: Policy and Experience. Basingstoke: Palgrave.

63. Hajian. H., B. Becerik-Gerber (2009) A research outlook for real-time project information management by integrating advanced field data acquisition systems and building information modeling, Proceedings of the International Workshop on Computing in Civil Engineering 2009, Austin, USA,

64. Hajian, H, & B. Becerik-Gerber, (2010) Scan to BIM: factors affecting operational and compu-tational errors and productivity loss, Proceedings of the 27th International Sympo-sium on Automation and Robotics in Construction (ISARC), 2010.
65. Hallberg, D., Stojanović, B., & Akander, J. (2012). Status, needs and possibilities for service life prediction and estimation of district heating distribution networks. Structure and Infrastructure Engineering, 8(1), 41–54. doi:10.1080/15732470903213740
66. Hawksworth, J. (2000) 'Implications of the Public Sector Financial Control Framework for PPPs' in The Private Finance Initiative: Saviour, Villain or Irrelevance. Commission on Public Private Partnerships,WP 1. London: Institute of Public Policy Research.
67. Heald, D. (2003) Value for Money Test and Accounting Treatment in PFI Schemes, Accounting, Auditing and Accountability Journal. 16: 3 pp342 – 71.
68. Hellowell, M. (2011). Money for Nothing : Political Journal.
69. Hellowell, M., & Vecchi, V. (2012). An Evaluation of the Projected Returns to Investors on 10 PFI Projects Commissioned by the National Health Service. Financial Accountability and Man, 28(February).
70. Henjewele, C., Sun, M., & Fewings, P. (2011). Critical parameters influencing value for money variations in PFI projects in the healthcare and transport sectors. Construction Management and Economics, 29(8), 825–839. doi:10.1080/01446193.2011.592204
71. HM Treasury, Private Finance Panel, (1995). Private opportunity, public benefit—progressing the private finance initiative. HMTreasury, London, November
72. HM Treasury, (2000). Public–Private Partnerships—The Government's Approach. The Stationery Office, London, April
73. HM Treasury, (2002). Press Release 74/02, 24 July
74. HM Treasury. (2003a). The Green Book—Appraisal and evaluation in central government. London: TSO.
75. HM Treasury. (2003b). PFI: Meeting the investment challenge. Norwich: HMSO.
76. House of Commons Treasury Committee, 2000. The private finance initiative. Fourth Report, Session 1999–2000, HC147, HMSO, London, 20 March.
77. Huber. D., B. Akinci, A. Adan, E. Anil, B. Okorn, X. Xiong, (2011) Methods for automatically modeling and representing as-built building information models, Proceedings of the NSF CMMI Research Innovation Conference.
78. Hurst, R., Williams, B., & Lay, M. (2005). Whole Life Economics of Building Services. International Facility and Property Information.
79. Ibid. & Sitzabee W.E., (2009). Data Integration of Pavement Markings: A Case in Transportation Asset Management. Journal of Computing in Civil Engineering 23, no. 5. 288–93.
80. ISO. (2002). Buildings and Constructed Assets -Service life planning Part 3: Performance Audits and Reviews
81. ISO. (2003). Systems Engineering -A guide for the application of ISO / IEC 15288 (System lifecycle processes).
82. ISO. (2006). Buildings and Constructed Assets -Service life planning Part 7: Performance evaluation for feedback of service life data from practice.
83. ISO. (2008). PAS 55-1: 2008 Asset Management
84. ISO. (2008a). Buildings and Constructed Assets -Service life planning Part 5: Lifecycle Costing.
85. ISO. (2008b). Buildings and constructed assets — Service-life planning Part 9: Guidance on assessment of servicelife data.
86. ISO. (2009). ISO 31000: 2009 Risk Management -Principles and guidelines. Ed 1.
87. ISO. (2010) ISO 29481-1:2010: Building InformationModeling—Information Delivery Manual — Part 1:Methodology and Format.

88. ISO. (2010). Buildings and Constructed Assets -Service life planning Part 10: When to assess functional performance.

89. ISO (2014b). Asset Management Management Systsems -Requirements.

90. Jernigan. F. (2007). Big BIM, little bim: the practical approach to building information model-ing; integrated practive done the right way, Aufl, 1, 4Site Press, Salisbury.

91. Kabir, G., Sadiq, R., & Tesfamariam, S. (2013). A review of multi-criteria decision-making methods for infrastructure management. Structure and Infrastructure Engineering, 10(9), 1176–1210. doi:10.1080/15732479.2013.795978

92. King, N,. (1998). Template Analysis. In D.G. Symon & P.C. Cassell (eds). Sage Publications Ltd.

93. Kintoye, A., Beck, M. and Hardcastle, C. (2002) Framework for Risk Management and Management of PFI Projects, Final Report, EPSRC/DTI, Glasgow: Glasgow Caledonian University.

94. Kirk .S. J and Dell'Isola (1995). A J Lifecycle Costing for design professionals (New York: McGraw-Hill).

95. Kirkham, R. J. (2002). A Stochastic Whole Life Cost Model for an NHS Acute Care Hospital Building.

96. Kirkham, R. J., & Boussabaine, a. H. (2005). Forecasting the residual service life of NHS hospital buildings: a stochastic approach. Construction Management and Economics, 23(5), 521–529. doi:10.1080/0144619042000326729

97. Klammt, F., (2001). Financial Management for Facility Managers. In TEICHOLZ E., ed. Facility Design and Management Handbook, New York: McGraw-Hill Companies Inc., pp. 5.1-5.37.

98. Klein. L. , N. Li, B. Becerik-Gerber, (2012) Image-based verification of as-built documentation of operational buildings, Autom. Constr. 21. 161–171

99. Klijn, E. H. and Teisman, G. R. (2000) 'Governing Public – Private Partnerships: Analysing and Managing the Process and Institutional Characteristics of Public – Private Partnerships' in S. P. Osborne (ed.) Public Private Partnerships: Theory and Practice in International Perspective. London: Routledge.

100. Kruger. N.A. (2012). To kill a real option -Incomplete contracts, real options and PPP. Transportation Research. Vol 46. 1359-1371.

101. Lair, J. and Chevalier (2002) Failure Mode Effect And Criticality Analysis For Risk Analysis (Design) and Maintenance Planning (Exploitation), Proceedings of 9th International Conference on Durability of Building Materials and Components, CSIRO, Brisbane, Australia

102. Lair, J., & Chevalier, J.-L. (2002). Service life assessment of building products by data fusion. Revue Française de Génie Civil, 6(3), 421–431. doi:10.1080/12795119.2002.9692377

103. Leite. F. , A. Akcamete, B.Akinci, G. Atasoy, S. Kiziltas (2011). Analysis ofmodeling effort and impact of different levels of detail in building information models, Autom. Constr. 20 601–609

104. Liebich. T. , C.-S. Schweer, S. Wernik, (2011) Die Auswirkungen von Building Information Modeling (BIM) auf die Leistungsbilder und Vergütungsstruktur für Architekten und Ingenieure sowie auf die Vertragsgestaltung, BBSR, BBR.

105. Liu.X , M. Eybpoosh, B. Akinci, (2012) Developing As-built Building Information Model using construction process history captured by a laser scanner and a camera, Proceedings of Construction Research Congress 2012: Construction Challenges in a FlatWorld, West Lafayette, USA,

106. Lin, Y.H., Liu, Y.S., Gao, G., Han, X.G., Lai, C.Y., & Gu, M. (2013). The IFC-based path planning for 3D indoor spaces. Advanced Engineering Informatics, 27(2), 189–205. doi:10.1016/j.aei.2012.10.001

107. Maintenance of mechanical services Maintenance and Renewal in Educational Buildings (1990). Bulletin No. 70 (London: Department of Education and Science)

108. Makridakis, S., Hibon, M., & Moser, C. (1979). Accuracy of Forecasting : An Empirical Accuracy Investigation, 142(2), 97–145.

109. Marteinsson, B. (2003). Durability and the factor method of ISO 15686-1. Building Research & Information, 31(6), 416–426. doi:10.1080/0961321032000105412

110. Meade, N. (2000). Evidence for the Selection of Forecasting Methods, 535(May 1999).

111. Meade, N. (2010). Oil prices — Brownian motion or mean reversion? A study using a one year ahead density forecast criterion. Energy Economics, 32(6), 1485–1498. doi:10.1016/j.eneco.2010.07.010

112. Mill. T , A. Alt, R. Liias (2013) Combined 3D building surveying techniques — terrestrial laser scanning (TLS) and total station surveying for BIM data management purposes, J. Civ. Eng. Manag. (iFirst 1-10, Published online: 24 Oct 2013)

113. Minow, M. (2003). Public and private partnerships: Accounting for the new religion. Harvard Law Review, 116, 1229–1237

114. Mommers, B. (2014). The Crossover Revolution. Geospatial World. Vol. March 2014. 62–63.

115. Montgomery, D.C., & Runger (2002). Applied Statistics and Probability for Engineers. Third Edition. John Wiley & Sons.

116. Motamedi. A., A. Hammad (2009). Lifecycle management of facilities components using radio frequency identification and building information model, J. Inf. Technol. Constr. (ITcon) 14. 238–262

117. Motawa. I. & Almashad. A., (2013). A knowledge based BIM system for building maintenance. Automation in Construction 29. 173-182.

118. Murphy, M., McGovern, E. and Pavia, S. (2007). Parametric vector modelling of laser and image surveys of 17th century classical architecture in Dublin. A paper presented at The 8th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST, Cyprus

119. Natukunda C.M, Pitt. M & Nabil. A. (2013) Understanding the outsourcing of facilities management services in Uganda. Hournal of Corporate Real Estate. Vol 15. 150-158.

120. NACUBO (1991). Managing the Facilties Portfolio. NACUBA, Washington DC.

121. National Audit Office, 2000b. The Financial Analysis for the London Underground Public–Private Partnerships, HC 54, 2000–2001. The Stationery Office, London, 15 December

122. National Audit Office, 2001a. Innovation in PFI Financing: The Treasury Building Project, HC 328, 2001–2002. The Stationery Office, London, 9 November

123. National Audit Office, 2001b.Managing the Relationship to Secure a Successful Partnership in PFI Projects, HC 375, 2001–2002. The Stationery Office, London, 29 November

124. Neve, T. & Selman, J., (2002). How much should we really spend on recapitalisation? Proceedings of the IFMA World Workplace Conference, Toronto, Ontario, October. 381-396

125. Partnerships UK (2005) Schools PFI—Post Signature Review. Phase 2 Report, Partnership UK, London. Partnerships UK (2006) Report on Operational PFI, Partner-ships, UK on behalf of HM Treasury, March. Partnerships UK (2010) Growing Demand, available at http://www.partnershipsuk.org.uk (accessed 30 September 2010).

126. Pas, B. S. I. (2008). PAS 55 Assessment Methodology (PAM).

127. Pickard, Jim (2 September 2008), PFI deals 'not doing a good job'. Financial Times (London), retrieved 11 June 2015

128. Philips, E.M. & Pugh, D.S. (2010). How to get a PhD: A handbook for students and their supervisors. Fifth edition. McGraw Hill. Open University Press.

129. Pitt, M., Collins, N. and Walls, A. (2006) The private finance initiative and value for money. Journal of Property Investment and Finance, 24(4), 363–73.

130. Pollock, A., Price, D. and Player, S. (2007) An examination of the UK Treasury's evidence base for cost and time over-run data in UK value-for-money policy and appraisal. Pub-lic Money and Management, 27(2), 127–34.

131. Presnak, R. & Yee, B., (2014). Life extension -The benefits are real. PennWell Corporation. Barrington, United States.

132. Qamar, S. Z., Sheikh, a. K., Arif, a. F. M., Younas, M., & Pervez, T. (2008). Monte Carlo simulation of extrusion die life. Journal of Materials Processing Technology, 202(1-3), 96–106. doi:10.1016/j.jmatprotec.2007.08.062

133. Raslan R.M.S., (2010). Performance Based Regulations: The Viability of the Modelling Approach as a Methodology for Building Energy Compliance Demonstration. *Doctoral Thesis*. Department of Environmental Design and Engineering. The Bartlett School of Graudate Studies. University College London.

134. Redmond. A., Hore. A., Alshawi. A., & West. R., (2012) Exploring how information exchanges can the enhanced through Cloud BIM, Autom. Constr. 24. 175–183

135. Reindorp, M.J., & Fu, M.C. (2011) Capital Renewal as a real option. European Journal of Operational Research. 109-117.

136. Reynaers, A.M., & De Graaf, G. (2014). Public Values in Public–Private Partnerships. International Journal of Public Administration, 37(2), 120–128. doi:10.1080/01900692.2013.836665

137. Richardson. S, Kefford. A, & Hodkiewicz. M., (2013). Optimised asset replacement strategy in the presence of lead time uncertainty. Int. J. Production Economics. 141. 659-657.

138. RICS (2009). BuildingMaintenance: Strategy, Planning and Procurement, Royal Institution of Chartered Surveyors, London.

139. Rush, S.C., 1991. Managing the facilities portfolio: A practical approach to institutional facility renewal and deferred maintenance. National Association of College and University Business Officers, Washington, DC.

140. Saxon, R.G., (2013). Growth through BIM. *Construction Industry Council*.

141. Selman, J. R. (2003). Creating a defensible recapitalisation programme. Journal of Corporate Real Estate, 5(2), 115–125. doi:10.1108/14630010310812055

142. Serratella, S. & Wang, G. (2008). Current practices in condition assessment of aged ships and floating offshore structures. 3-35. Woodhead Publishing Series in Civil and Strucutral Engineering.

143. Settanni, E., Newnes, L. B., Thenent, N. E., Parry, G., & Goh, Y. M. (2014). A through-life costing methodology for use in product–service-systems. International Journal of Production Economics, 153, 161–177. doi:10.1016/j.ijpe.2014.02.016

144. Shafiq. M.T. , J. Matthews, S.R. Lockley, (2013) A study of BIM collaboration requirements and available features in existing model collaboration systems, ITcon 18. 148–161.

145. Shaoul, J. (2009) Using the private sector to finance capital expenditure: the financial realities,. in Akintoye, A. and Beck, M. (eds) Policy, Finance and Management for Public-Private Partnerships, Wiley-Blackwell, Chichester, pp. 27– 46.

146. Shen, W., Hao, Q., & Xue, Y. (2012). A loosely coupled system integration approach for decision support in facility management and maintenance. Automation in Construction, 25, 41–48. doi:10.1016/j.autcon.2012.04.003

147. Silva, a., de Brito, J., & Gaspar, P. L. (2012). Application of the factor method to maintenance decision support for stone cladding. Automation in Construction, 22, 165–174. doi:10.1016/j.autcon.2011.06.014

148. Singh. V., N. Gu, X. Wang, (2011) A theoretical framework of a BIM-based multi-disciplinary collaboration platform, Autom. Constr. 20. 134–144.

149. Sitzabee W.E., (2013) A strategic assessment of infrastructure asset management modelling. Air and Space Power Journal. November -December 2013. 45-68

150. Smith, D.K., (2007). National BIM Standard, In: 6th Annual Federal Environmental Symposium, http://www.fedcenter.gov/_kd/go.cfm?destination=ShowItem&Item_ID=7430, Last accessed: January 2010

151. Smith. D.K. , M. Tardif, (2009) Building Information Modeling: A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Asset Managers, John Wiley & Sons, England.

152. Spackman, M. (2002). Public–private partnerships: lessons from the British approach. Economic Systems, 26(3), 283–301. doi:10.1016/S0939-3625(02)00048-1

153. Stacy, E. (2003). A broader view, (May).

154. Sterman, J. (1998). Playing the Maintenance Game.

155. Taleb, N.N., (2007). The Black Swan: the impact of the highly improbable. New York: Random House.

156. Talon, a., Boissier, D., & Lair, J. (2008). Service-life assessment of building components: application of evidence theory. Canadian Journal of Civil Engineering, 35(3), 287–300. doi:10.1139/L07-109

157. Tang. P., D. Huber, B. Akinci, R. Lipman, A. Lytle, (2010). Automatic reconstruction of as-built building information models from laser-scanned point clouds: a review of related techniques, Autom. Constr. 19. 829–843.

158. Tashakkori, A, & Teddie, C,. (2003). Handbook of Mixed Methods in Social & Behavioural Research. Thousand Oaks Calif. Sage Publications.

159. Tian, Z., Wong, L., & Safaei, N. (2010). A neural network approach for remaining useful life prediction utilizing both failure and suspension histories. Mechanical Systems and Signal Processing, 24(5), 1542–1555. doi:10.1016/j.ymssp.2009.11.005

160. Teicholz, E., (2004). Bridging the AEC technology gap. IFMA Facility Management Journal, March–April, 2004. http://www.graphicsystems.biz/gsi/articles/Bridging%20the%20AEC_FM%20Gap_r2.pdf

161. Tutt, D., & Harty, C. (2013). Journeys through the CAVE: The use of 3D immersive environments for client engagement practices in hospital design. Paper presented at the ARCOM, Reading

162. Ujjwal, B. (2011). Risk based life management of offshore structures and equipment. Engineering Doctorate Thesis.

163. Ujjwal, B., Vadim, S., & John, W. (2012). Journal of Quality in Maintenance Engineering Article information : Journal of Quality in Maintenance Engineering.

164. University of California, 2009. Accountability report. Oakland, CA.

165. U.S. GSA, (2009). GSA BIM Guide For Energy Performance, U.S. General Services Administration — Public Building Service, Washington.

166. Valentine, E. and Zyskowski, P., (2009). Models (BIM): How it Has Changed FM. Facility Management Journal, http://www.fmlink.com/ProfResources/Magazines/article.cgi?FMJ:fmj051409-1.html.

167. Valero. E., A. Adan, D. Huber, C. Cerrada, (2011) Detection, modeling, and classification of moldings for automated reverse engineering of buildings from 3D data, Proceed-ings of the International Symposiumon Automation and Robotics in Construction (ISARC).

168. Valero. E., A. Adan, C. Cerrada, (2012) Automatic construction of 3D basic-semanticmodels of inhabited interiors using laser scanners and RFID sensors, Sensors 12. 5705–5724

169. Vanier, D.J., 2001. Why industry needs asset management tools. Journal of Computing in Civil Engineering, 15.

170. Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. Automation in Construction, 38, 109–127. doi:10.1016/j.autcon.2013.10.023

171. Vose, D., (2008). Risk Analysis: a qualitative guide. Chicesterl Wiley 3rd ed.

172. Waheed. Z. & Fernie. S., (2009). Knowledge based facilities management, Facilities 27. 258–266

173. Wanous, M. (2000) A neurofuzzy expert system for competitive tendering in civil engineering, unpublished PhD thesis, The University of Liverpool

174. Watson. A., (2011) Digital buildings — challenges and opportunities, Adv. Eng. Inform. 25. 573-581

175. Williams, C. (2007). Research Methods, 5(3), 65–72.

176. Woodhouse, J. (2009). Managing Mature Assets, (Figure 1).

177. Woodhouse, J. (2011). Optimal Timing for Replacing Aging or Obsolete Assets, IET Asset, 1–10.

178. Woodhouse, J., & Fiam, M. A. (2013). Making the Business Case for Asset Life Extension, 1–5.

179. Woodhouse, T. (2012). The SALVO Project : Innovative approaches to decision-making for the management of aging physical assets, (February 2011), 1–11.

180. Wu, J-W., Hung., W-L & Chen., C-Y. (2013). Approximate MLE of the scale parameter of the first truncated Rayleigh distriution under the first failure-censored data. *Journal of Information and Optimisation Sciences*. p222-235

181. Wu, N., & Shih, S.-G. (2014). A BIM Inspired Supporting Platform for Architectural Design. Computer-Aided Design and Applications, 12(3), 327–337. doi:10.1080/16864360.2014.981463

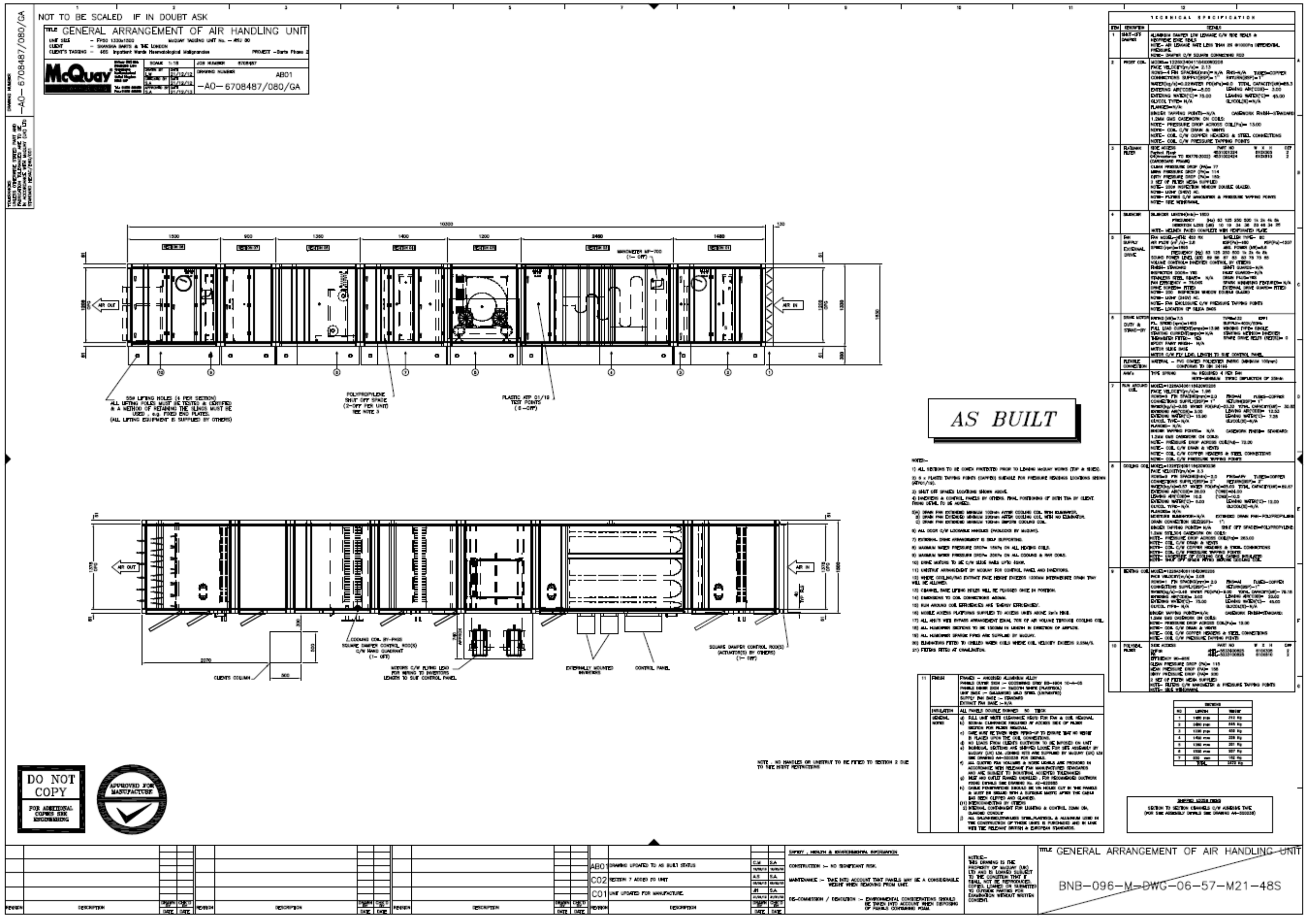
182. Xiong. X., A. Adan, B. Akinci, D. Huber, (2013) Automatic creation of semantically rich 3D buildingmodels from laser scanner data, Autom. Constr. 31. 325–337.

183. Zheng, J. Roehrich, J.K. and Lewis, M.A. (2008).The dynamics of contractual and relational governance: Evidence from long-term public-private procurement arrangements. Journal of Purchasing and Supply Management. 14(1): 43-54 Retrieved 21 October 2014

Appendix 1. Workflow Chart

Revit 2013		3ds Max 2014		Bentley MicroStation V8i		SketchUp 2013 Pro		Unity 3D (with meshes and textures only)	ArchiCAD 17 (only including 3D formats)		Navisworks Manage 2014		Vectorworks 2013	
Import	**Export**	**Import**	**Export**	**Import**	**Export**	**Import**	**Export**	**Import**	**Import**	**Export**	**Import**	**Export**	**Import**	**Export**
RVT	RVT	RVT	MAX	DGN	DGN	SKP	SKP	MB	PLN	PLN	NWD	NWD	IFC	IFC
IFC	IFC	FBX	CHR	IGES	IGES	DWG	DWG	MA	PLA	DWG	NWF	NWF	3DS	DXF
ADSK	FBX	DWG	FBX	XMT	XMT	DXF	DXF	JAS	BPN	DXF	NWC	NWC	IGES	DWG
	DWG	DXF	3DS	SAT	SAT	3DS	DAE	C4D	PLP	IFC	ZFC	DWF	SAT	DWF
	DXF	3DS	AI	CGM	CGM	DAE	FBX	BLEND	PLC	IFCXML	ZFS	DWFX	Rhino 3DM	3DS
	DGN	PRJ	ASE	STP	STP	DEM	KMZ	LXO	PCA	BIMX	WRL	FBX	Parasolid X_T	C4D
	SAT	AI	DAE	STL	STL	DDF	OBJ	FBX	BPC	SKP	WRZ	KML	SKP	DAE
	DWF	ASM	DWF	DGN	DGN	KMZ	WRL	DAE	DWF	KMZ	STL		DXF	FBX
	NWC	CATPART	DWG	DWG	DWG		XSI	Carrara	DXF	OBJ	STP		DWG	IGES
	gbXML	CGR	DXF	DXF	DXF			Lightwave	DWG	3DS	STEP		DWF	KML
		CATPRODUCT	FLT	XML	U3D			XSI	DGN	STL	PRT			SAT
		DAE	HTR		SVG			SKP	PLT	EPX	SLDPRT			VectorScript
		XML	IGS		WRL			WINGS	IFC	FACT	ASM			Rhino 3DM
		DEM	OBJ		LXO				IFCXML	WRL	SLDASM			Lithography
		DDF	PXPROJ		OBJ				IFCZIP	LP	SKP			Parasolid X_T
		DWG	SAT		FBX				SKP	U3D	SAT			
		DXF	STL		SKP				KMZ	ATL	RVM			
		FLT	W3D		KML				STL		3DD			
		HTR	WIRE		KMZ						RVT			
		IGE	WRL		DAE						RFA			
		IGES			JT						RTE			
		TGS									RCS			
		IAM									RCP			
		JT									NEU			
		MODEL									X_B			
		DLV4									MAN			
		DLV3									CV7			
		DLV									PTS			
		EXP									PTX			
		SESSION									JT			
		MDL									IPT			
		OBJ									IAM			
		PRT									IPJ			
		SAT									IGS			
		SHP									IGES			
		SKP									IFC			
		SLDPRT									FBX			
		SLDASM									FLS			
		STL									FWS			
		STEP									IQSCAN			
		STP									IQMOD			
		TRC									IQWSP			
		WIRE									DWG			
		WRL									DXF			
		WRZ									DWF			
		XML									DWFX			
											W2D			
											DGN			

Appendix 2. Example AHU Drawing



Appendix 3. Data Collection Sheet

Data Source Key
Invoice
Authorised Person (AP)
Building Management System (BMS)
O&M manual
Other Source

Where more than two colours are listed it is foreseen that there may be more than one data source available

University College London & HCP Social Infrastructure UK

Failure Data Collection Sheet

Asset - Air Handling Unit

UCL & HCP SAM Team: OUTTURN AHU DATA

1 component per line

Source	AP	AP	AP	BCIS	Invoice	Invoice	Invoice	Invoice	AP	O&M	O&M	O&M	AP
	General							AHU Data					
	Total Number of AHUs on Site	*Comission Date*	*Project*	*BCIS Region*	*Component*	*Description*	*Date of replacement*	*AHU ID/Number*	*Area served*	*Spec/ Manufacturer/ Model*	*AHU fan supply speed (rpm)*	*AHU fan supply air flow (m3/s)*	*Internal/ External?*
Example	154	01-Jan-02	Modus	London (Inner)	Cooling Coil	Cooling coil replacement to Supply AHU	01.01.2015	AHU 25	Operating Theatre	McQuay	2309	1.24	Internal
1				None									
2													

Source	BMS/ AP	BMS/ AP	BMS/ AP	AP	Invoice/AP	Invoice	Invoice	Invoice	Invoice	Invoice	Invoice	Invoice	Invoice	Invoice	Invoice	Invoice	Invoice	Sheet Calc
	AHU Data				Subcontractor Costs (net)					Service Provider On-Costs (gross)								Total
	Runtime per weekday (hours)	*Runtime Saturday (hours)*	*Runtime Sunday (hours)*	*Install/ Commission date*	*Subcontractor Name*	*Qty*	*Unit*	*Rate*	*Sub - Total (£)*	*Attendance / Security*	*Access*	*Cleaning*	*Prelims*	*Risk/ Contingency*	*Disposal*	*Management*	*Sub - Total (£)*	*Total (£)*
Example	9	9	6	01.01.2002	Wilson Electric	1	Number	1,142.00	1,142.00	50	0	0	0.00	0.00	150.00	230.00	430.00	1,572.00
1									0.00								0.00	0.00
2									0.00								0.00	0.00

Appendix 4. Letter to HCP Sites

intelligent
management
of assets

HCP
6 Middle Street
London EC1A 7PH
www.hcp.co.uk

Recipient Name
Recipient Address 1
Recipient Address 2
Recipient Address 3
Postcode
Date

Dear [insert SPV manager],

Ref: Strategic Asset Management Data Collection

You may recall at the HCP conference there were three presentations of work that we as a company are conducting with University College London (UCL). HCP is working in partnership with UCL to undertake research looking specifically at hospitals Heating and Ventilation (HVAC) Equipment.

The outcome of the research will contribute towards improved lifecycle expenditure planning for HVAC assets across the portfolio.

We would like your hospital and its input to be included in the research. This data is held by your hard FM provider. I would value your assistance in providing me with the HFM contact name and number. The research is focussed on air handling unit components and your support in obtaining the following simple information bullet pointed below.

1. AHU asset register;
2. AHU runtime list;
3. Construction completion and commission date;
4. AHU O&M drawings;
5. All planned and unplanned expenditure relating to AHU parts since the beginning of the project.

Please could you provide the HFM contact information requested as I would like to complete this exercise by the end of [month]. Once I have the contact information I shall follow up and obtain the information and keep you informed. I am happy to make a site visit if required.

Should you have any questions please do not hesitate contact me.

I look forward to hearing from you.

Best regards,

Amir Nabil
Data Analyst and Doctoral Researcher
For and on behalf of HCP Management Services Limited and University College London

HCP
6 Middle Street | London | EC1A 7PH
+44 (0) 75 2563 8812 | +44 (0) 20 7600 2900 | www.hcp.co.uk
nabil@hcp.co.uk

HCP Management Services Limited
Registered in England No 03819468
Registered Office: 8 White Oak Square, London Road, Swanley, Kent, BR8 7AG

Appendix 5. Head of Asset Management Contact with Hospital Sites

Sat 01/08/2015 18:01

Babajide Ogunniyi

SAM - Assistance with information Hinchingbrooke Treatment Centre / Peterborough Hospital

To Clare Parkinson

Cc Amir Nabil; Chris Hatch; Sarah Westwood [redacted]

Clare, [redacted]

I hope you are well? By way of this email, can I introduce you to Amir who is a Lifecycle Data Analyst / Modeller in the SAM team. Amir is doing his PhD in risk based lifecycle modelling and he needs your help with gathering asset performance data for Air Handling Units to add credibility to his thesis. Including:

- Running time
- Cost data for parts
- O&M information

I know you are very busy but hopefully given your good relationship with the Service Provider they can assist with this information need. Amir is likely to be in contact and I would appreciate any assistance you can offer.

Regards,

Babajide Ogunniyi
Head of Asset Management

HCP
6 Middle Street | London | EC1A 7PH
+44(0)7894585747|+44(0)2076002900 |www.hcp.co.u[redacted]

Partnerships Awards 2015 GOLD AWARD WINNER SPV MANAGEMENT COMPANY OF THE YEAR

Appendix 6. Instances where Hospitals Could not be Included in the Study

Wed 26/08/2015 11:33

[redacted]

To Amir Nabil

Cc Babajide Ogunniyi

You replied to this message on 26/08/2015 11:43.

Hello Amir,

Afraid as I suspected Brookfield are not being forth coming with any data, they haven't even acknowledged the request. Looking at the data we have, there hasn't been any lifecycle claims submitted for any AHU's, I can ask if they have run hours but wouldn't be hopeful for a response and can offer my log in to the electronic O&M's for the manufacturers data?

Kind regards,

[redacted]

HCP

[redacted]

www.hcp.co.uk

HCP Social Infrastructure (UK) Ltd is registered in England and Wales. Registration number: 2658304. Registered office: 8 White Oak Square, London Road, Swanley, Kent, BR8 7AG.

Appendix 7. Contractual Area Weighting Percentage Example – Cardiac Unit

Functional Area	Functional Area Weighting Services (%)	Functional Area Weighting Interim Services (%)
A1. RLH ACAD Centre	4.000%	1.600%
A2. RLH ACAD - Endoscopy	4.000%	1.600%
A3. RLH ACAD Haematology	2.000%	0.800%
A4. RLH Accident & Emergency	19.000%	7.600%
A5. RLH Adult Inpatient Unit RLH	5.000%	2.000%

Appendix 8. Contractual Unit Weighting Percentages

1. FUNCTIONAL AREA: SBH CARDIAC UNIT

FU Unique Description	Functional Unit	Room Number		Functional Unit Weight (%)		Key Functional Unit
		Interim	Steady State	Interim	Steady State	
	Clinical					
	2.03: Cardiac Day Case & Catheter Labs					
Catheter Suite	Catheter Suite	QE/-1/8, QE/-1/13, QE/-1/15, QE/-1/18, QE/-1/46, QE/-1/47, QE/-1/56, QE/-1/68, QE/-1/61, QE/-1/57, TB/0/85, TB/0/87, TB/2/66,	2.03/0110, 0230, 0386, 0388	8.0%	9.0%	
Catheter Labs (a)	Catheter Labs	QE/-1/7	2.03/0130,	5.0%	5.%	
Catheter Labs (b)	Catheter Labs	QE/-1/50	2.03/0140,	5.0%	4.50%	

Appendix 9. Contractual Failure Event Categories

Failure Event Category	Importance	Service Deficiency Points	Service Failure Event Deduction Percentage	IS Failure Event Deduction Percentage
A	Routine	1	5%	5%
B	Important	2	10%	10%
C	Major	6	30%	30%
D	Unavailable and Used	20	50%	40%
E	Unavailable and Not Used	20	100%	75%

Appendix 10. Install Completion Document

McQuay International

SITE INSTALL
COMPLETION DOCUMENT

AHU SERIAL NUMBER	6708487
UNIT NUMBER	02 S
CLIENT	SKANSKA
PROJECT NAME	BARTS HOSPITAL

DELIVERY	YES	NO
UNITS DELIVERED WITHOUT DAMAGE	✓	

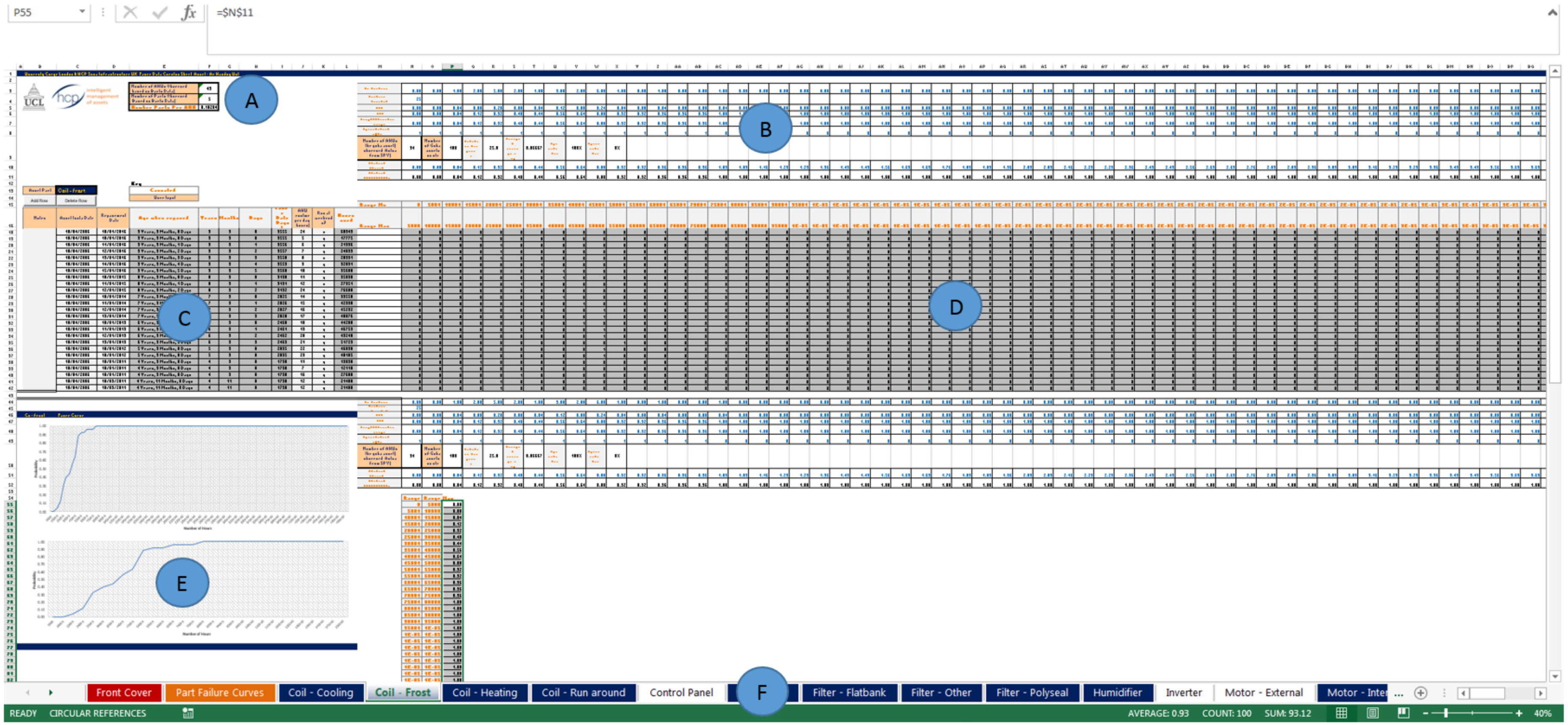
OFFLOAD	YES	NO
DAMAGES DURING TRANSPORT TO SITE		✓
DAMAGES DURING OFFLOAD		✓
DAMAGES DURING TRANSPORT TO PLANTROOM		✓
COMMENTS		

INSTALLATION	YES	NO
DAMAGES DURING INSTALL		✓
DAMAGES DURING JOINTING		✓
DAMAGES DURING STACKING		✓
DAMAGES BY OTHERS		✓
UNIT INSTALLED IN CORRECT LOCATION	✓	
UNIT INSTALLED IN CORRECT ORIENTATION	✓	
TRANSIT BRACKETS REMOVED	✓	
PROTECTION SUPPLIED AND FITTED	✓	
PRE-COMMISSIONING COMPLETED	✓	
COMMENTS Generally – Pad Locks on Doors Had no affect.		

COMPLETION
THE UNIT HAS BEEN SUPPLIED AND INSTALLED AT SITE WITH NO DAMAGES TO REPORT FROM OUR CLIENT.
ANY DAMAGES REPORTED HAVE NOW BEEN RECTIFIED AND THE UNIT CONFORMS TO OUR CONTRACT REQUIREMENTS

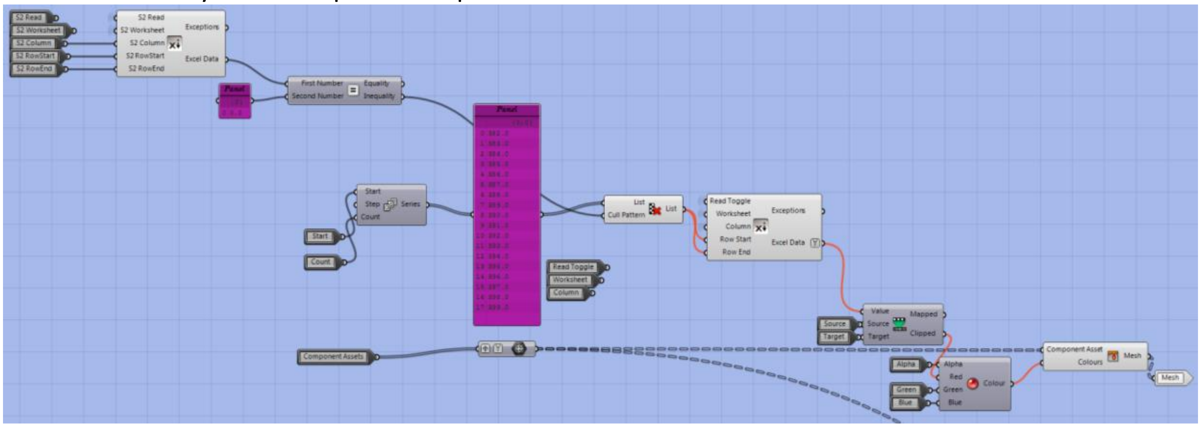
		DATE
CLIENTS NAME	[redacted]	5-11-08
SIGNATURE		
ENGINEERS NAME		5/11/08
SIGNATURE		

Appendix 11. Lifecycle Model Component Tab



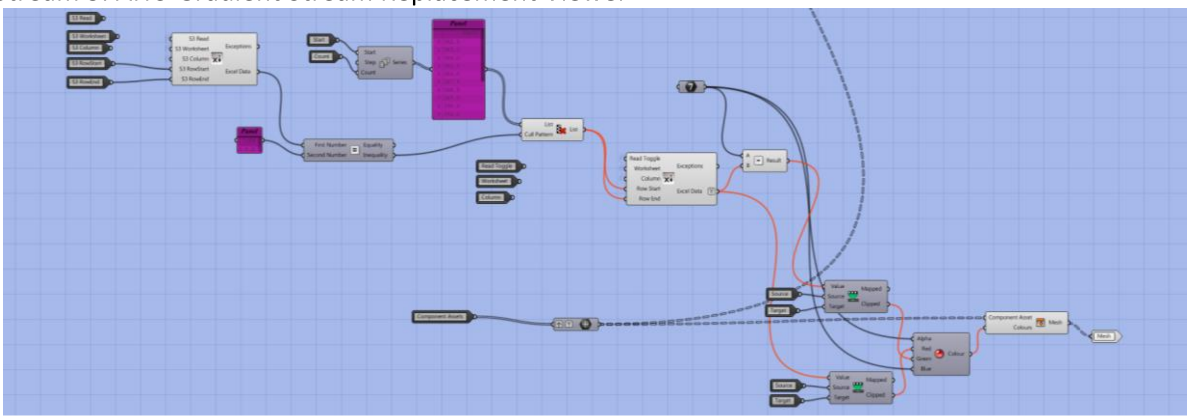
Appendix 12. Grasshopper Logic Diagrams

Stream 2: AHU System Component Replacement Viewer



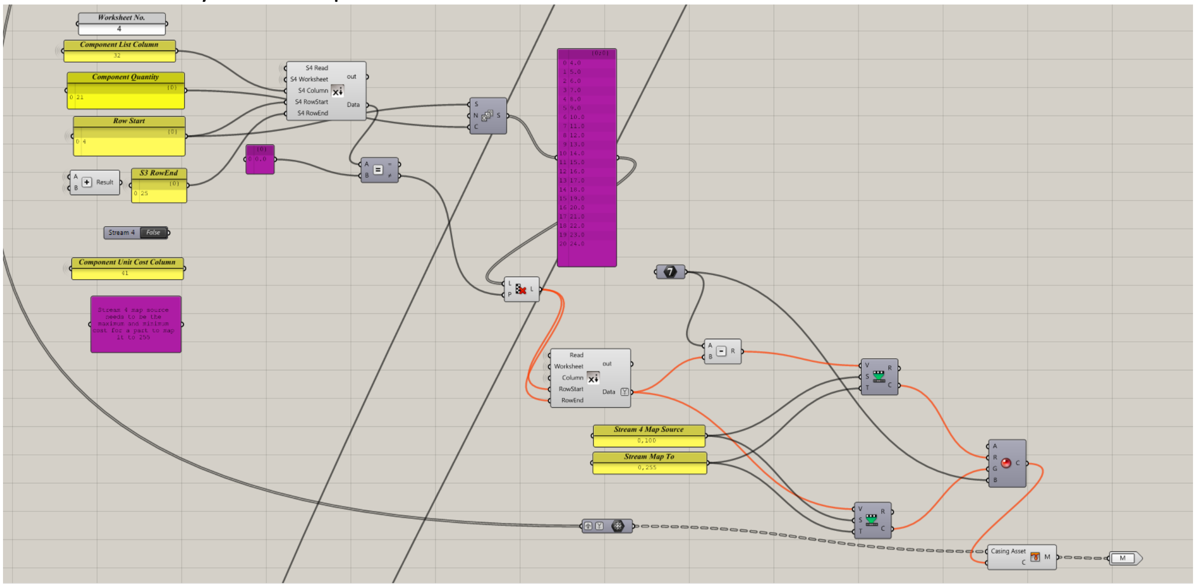
Much the same as stream 1, stream 2 receives the lifecycle model as an input but a different set of data. The logic sifts through the imported data associated with the components within the AHU being modelled and ignores the components which are not included in its configuration. Otherwise known as culling, the process involves stepping through the components and where included, these parts are visually mapped based on their own unique maxima and minima. This colour feeds forward and is assigned to the appropriate casing asset input geometry. The merging of geometry and data occurs prior to outputting the meshes to the model. However, in this case, rather than one mesh as in stream 1, stream two comprises all of the component assets associated and maps them all simultaneously. Doing this saves time, memory and model complexity, while increasing speed and responsiveness of the model.

Stream 3: AHU Gradient Stream Replacement Viewer



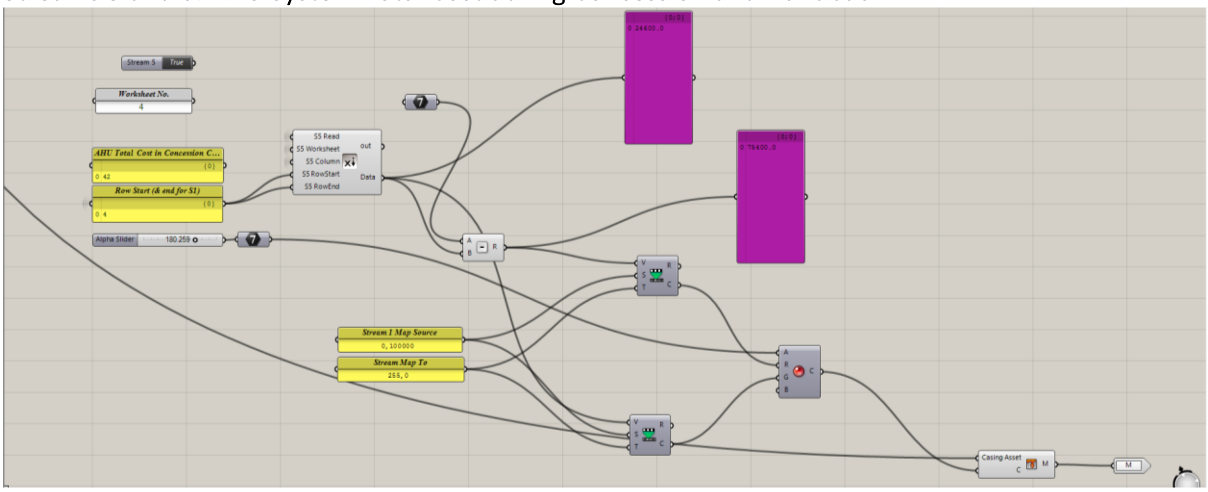
Stream 3 follows a similar logic to stream 2, however, in order to generate the gradient colour, the maxima and minima mapping is slightly more intricate. The data import, culling and mesh assignment/ generation process remains the same.

Stream 4: AHU System Component Unit Cost viewer



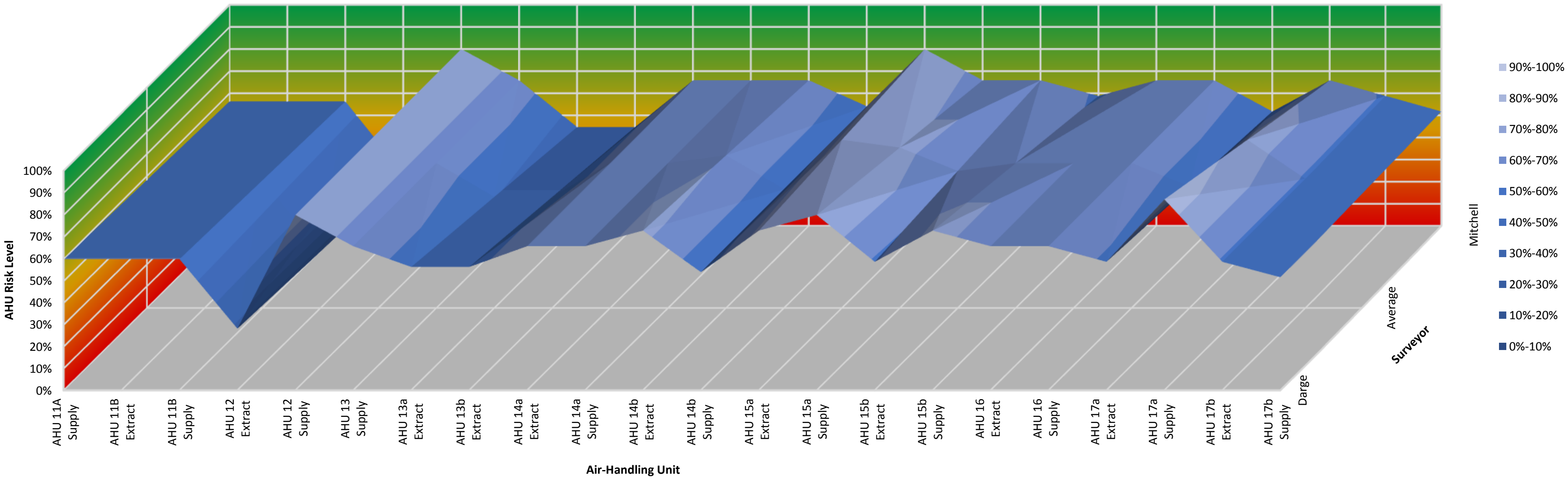
Stream 4 was concerned with viewing the cost of the parts. This merged aspects of the previous streams; taking the static (i.e. singular cost – rather than time based gradient seen previous) cost data in the lifecycle model and applying across multiple components (as opposed to the AHU system as a whole as seen previous) through culling rows in the lifecycle model that were not necessary. The streaming source shall be dependent and constantly fluctuating due to financial variations in part costs in future. In other words, the maxima and minima costs with which to map the values to create the colour gradient visual will change over time, as parts naturally increase in cost. Thus, the static mapping value seen in previous data streams (the binary code from 0-1) is not as constant in this data stream because it is visualising index linked components. Where the components are in real prices, this maxima minima fluctuation is still seen to be true because with the updating of the cost data as more part failures are recorded, the database limits shall change over time.

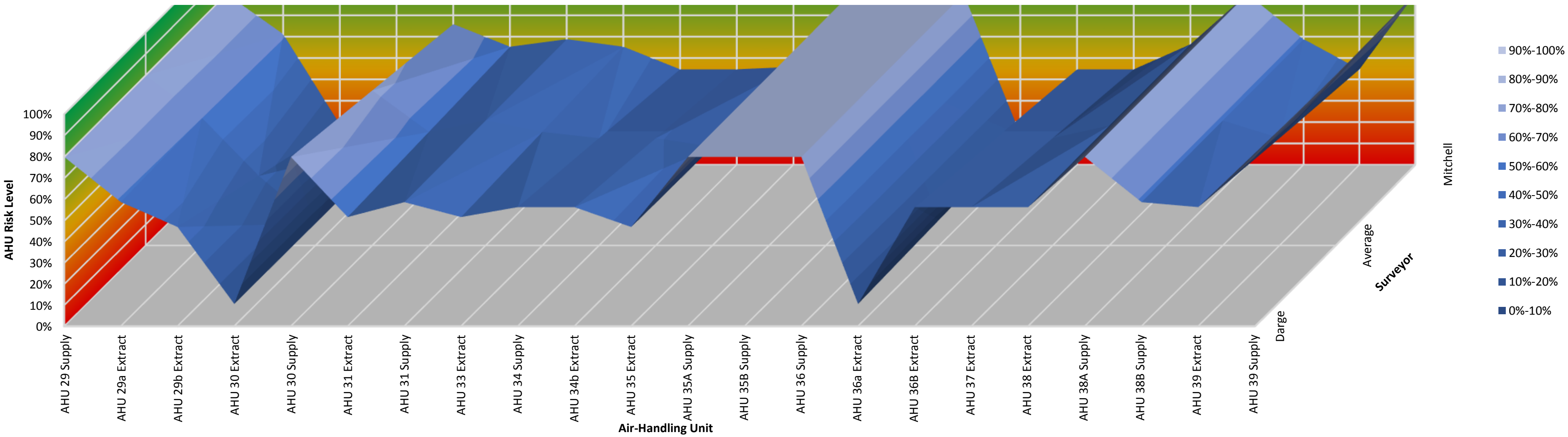
Streams 5 and 6: AHU System Total Cost during Concession and Handback

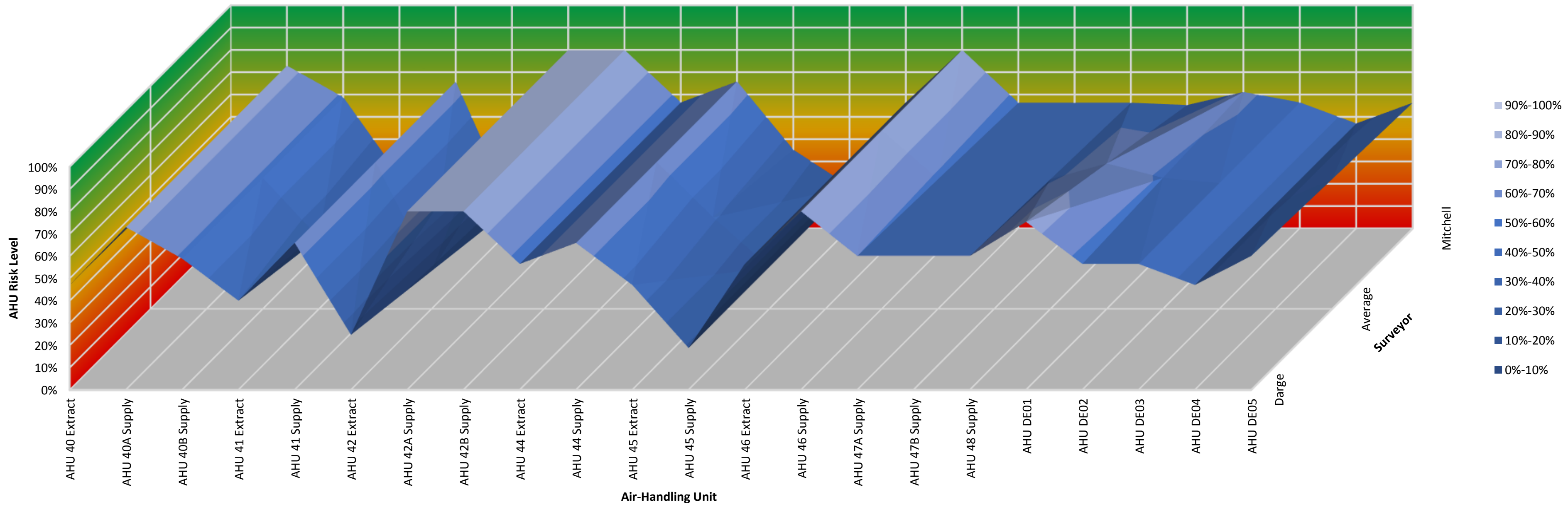


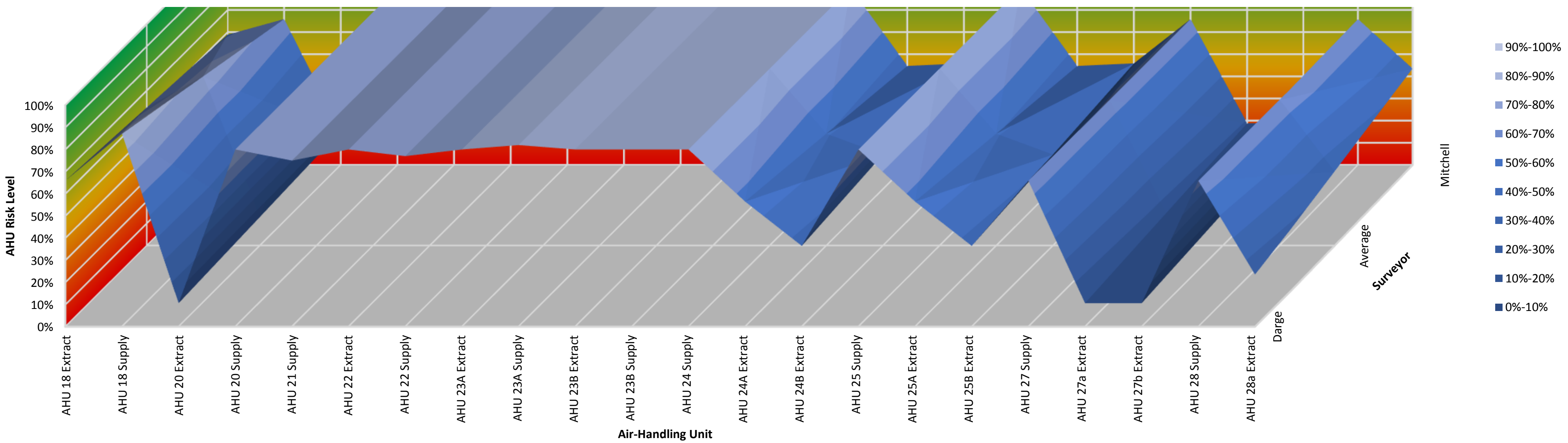
Streams 5 and 6 aim to show the user the high ticket items throughout the concession period and handback period respectively. The logic pulls the total costs from the lifecycle model associated with all the components within a single AHU system and displays the result on an AHU system level to illustrate the hotspots in terms of investment over the coming years. More crucially, the handback period visualisation follows the same logic but displays the costs *outside* of the concession period (the *handback* period). This time period can be described as time where the is no income from the client through the lifecycle aspect of the UC (or the UC in general in fact) but where there is still an expectation of 'good' equipment performance and any failures during this period could be billable to the MSP. Through visualising these top level costs, decision-makers can instruct further analysis or smoothing of figures in key areas to satisfy future DSCRs if necessary. Again, in a similar style to stream 4, streams 5 and 6 both have to be remapped to take account for maxima and minima costs in their periods respectively.

Appendix 13. AHU Engineering-Risk Survey Graphs

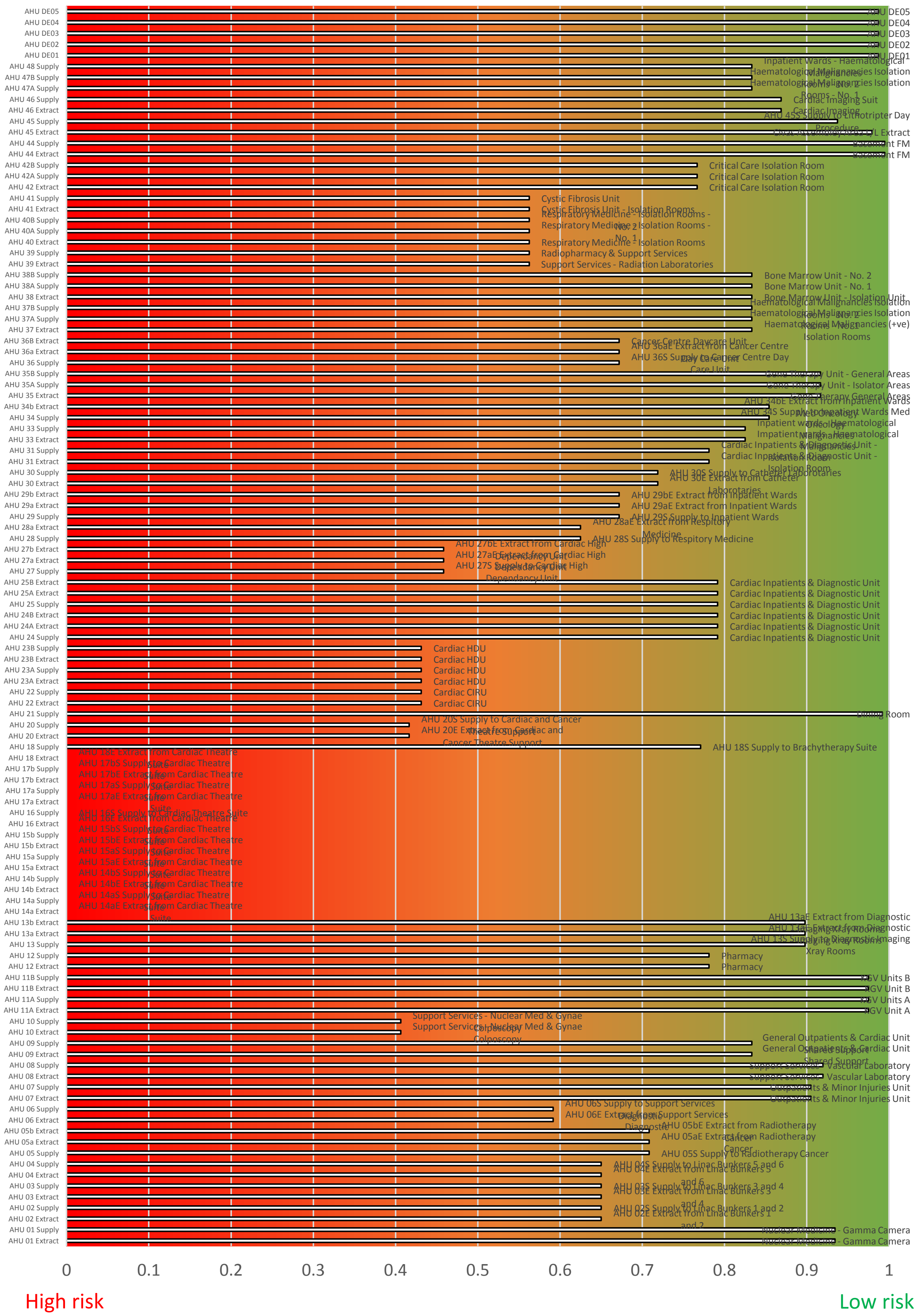




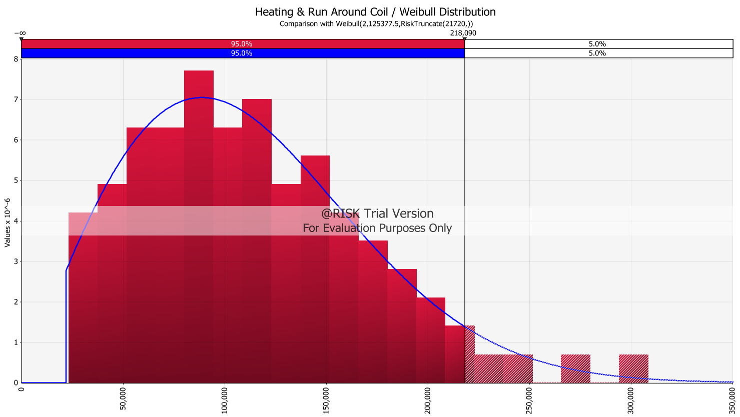

AHU Risk Level
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
AHU 40 Extract
AHU 40A Supply
AHU 40B Supply
AHU 41 Extract
AHU 41 Supply
AHU 42 Extract
AHU 42A Supply
AHU 42B Supply
AHU 44 Extract
AHU 44 Supply
AHU 45 Extract
AHU 45 Supply
AHU 46 Extract
AHU 46 Supply
AHU 47A Supply
AHU 47B Supply
AHU 48 Supply
AHU DE01
AHU DE02
AHU DE03
AHU DE04
AHU DE05
Air-Handling Unit
Darge
Average
Mitchell
Surveyor
90%-100%
80%-90%
70%-80%
60%-70%
50%-60%
40%-50%
30%-40%
20%-30%
10%-20%
0%-10%

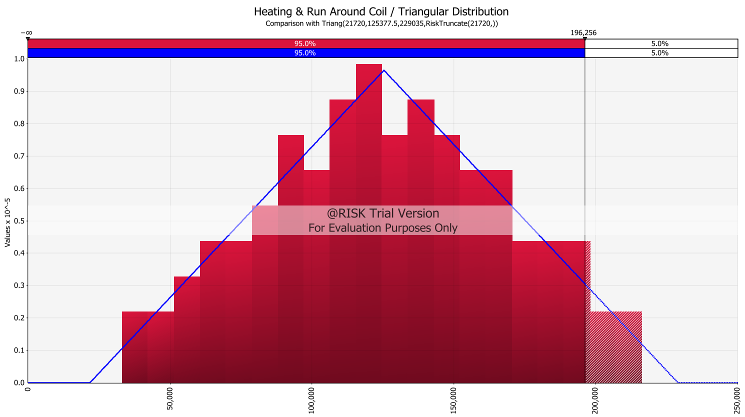

AHU Risk Level
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
AHU 18 Extract
AHU 18 Supply
AHU 20 Extract
AHU 20 Supply
AHU 21 Supply
AHU 22 Extract
AHU 22 Supply
AHU 23A Extract
AHU 23A Supply
AHU 23B Extract
AHU 23B Supply
AHU 24 Supply
AHU 24A Extract
AHU 24B Extract
AHU 25 Supply
AHU 25A Extract
AHU 25B Extract
AHU 27 Supply
AHU 27a Extract
AHU 27b Extract
AHU 28 Supply
AHU 28a Extract
Air-Handling Unit
Darge
Average
Mitchell
Surveyor
90%-100%
80%-90%
70%-80%
60%-70%
50%-60%
40%-50%
30%-40%
20%-30%
10%-20%
0%-10%

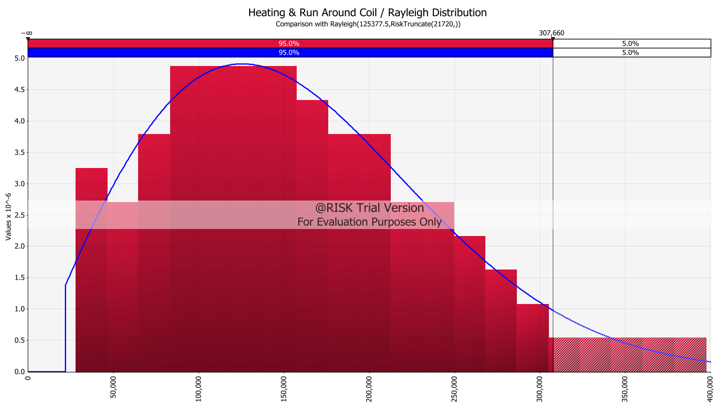
Appendix 14. Paymech Risk Level Results



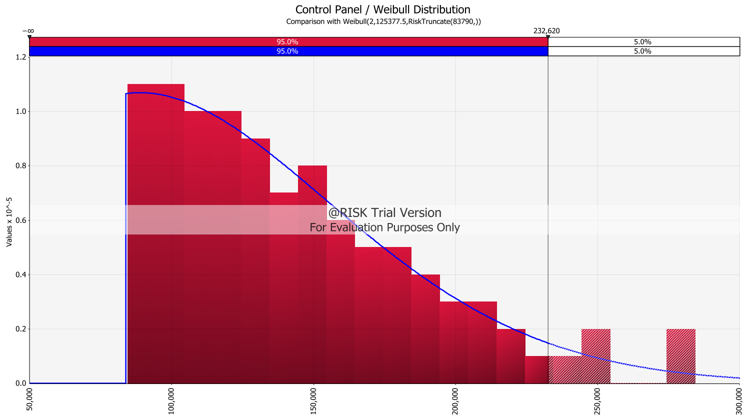
Appendix 15. Monte Carlo-Simulated Distributions and Statistics

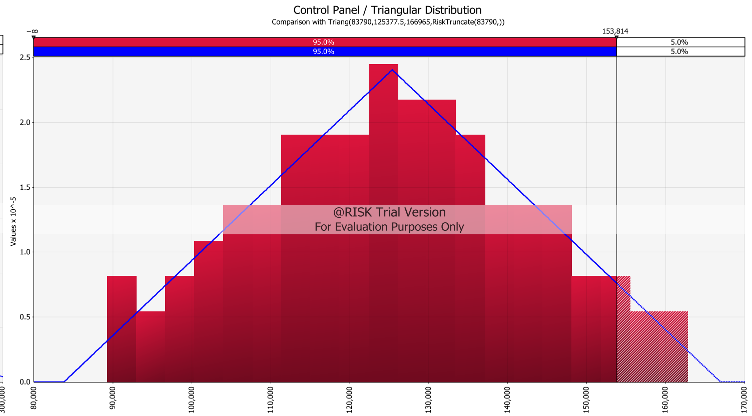


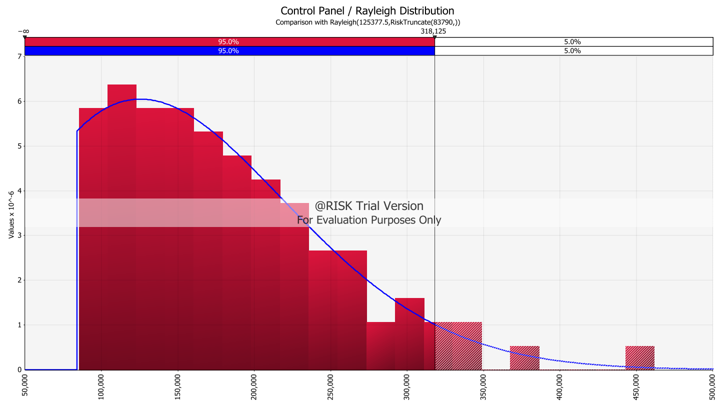




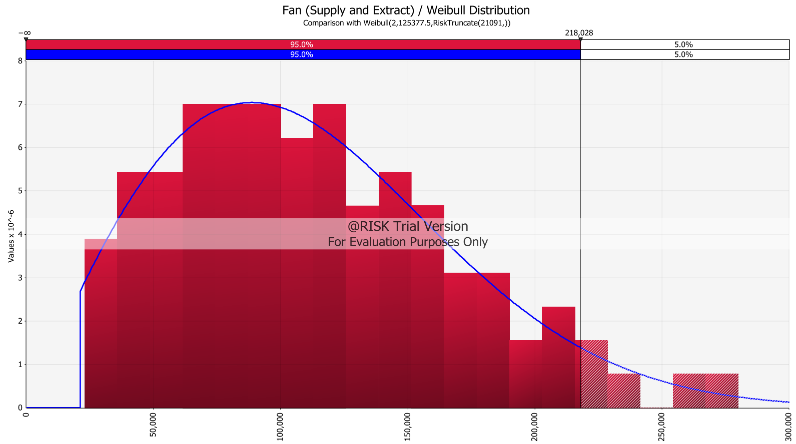
Distribution	Lifecycle Pseudonym	Risk Profile	Parameters						Min	Max (95% perc.)	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			y	α	β	Min life	Mean Life	Max Life							
Weibull	Conservative	Low	0	2	125,378	n/a	n/a	n/a	22063.87	216441.3	114298.7	57219.04	3.27+E09	0.7531979	3.517145
Triangular	Balanced	Medium	n/a	n/a	n/a	21,720	125,378	229,035	27338.87	193745.5	125282.2	42296.52	1.78+E09	-0.0212347	2.41119
Rayleigh	Optimistic	High	n/a	n/a	125,378	n/a	n/a	n/a	23374.66	301497	158907.8	80018.28	6.40+E09	0.5868077	2.923434

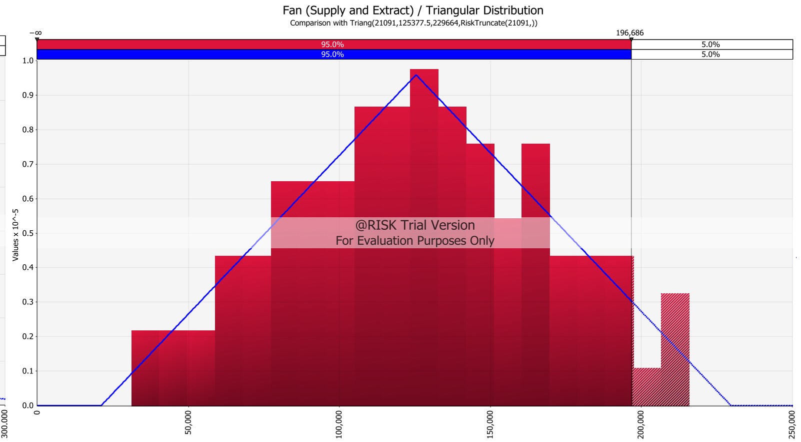


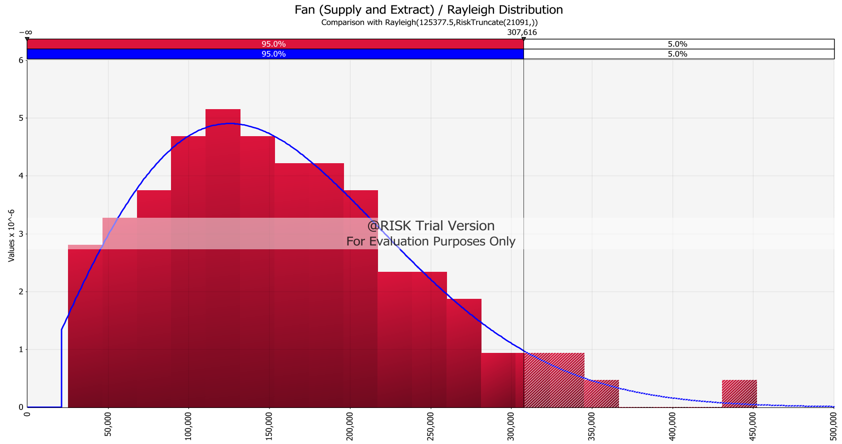




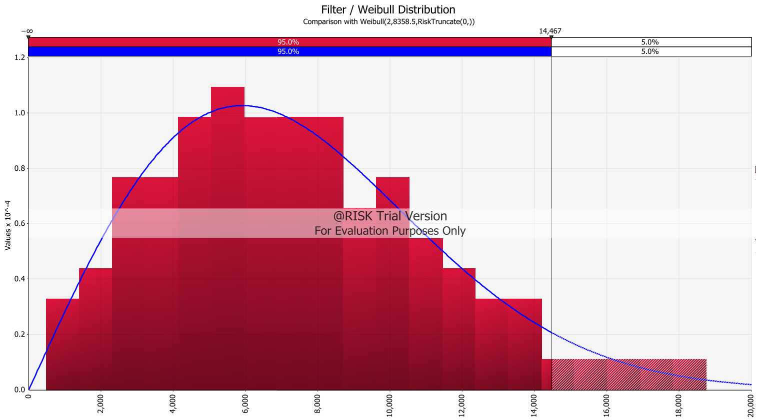
Distribution	Lifecycle Pseudonym	Risk Profile	Parameters						Min	Max (95% perc.)	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			γ	α	β	Min life	Mean Life	Max Life							
Weibull	Conservative	Low	0	5	125,378	n/a	n/a	n/a	83849.9	226785	143411.8	45264.18	2.04+E09	0.941577	3.477672
Triangular	Balanced	Medium	n/a	n/a	n/a	83,790	125,378	166,965	87257.63	152622.4	125331.6	17089.08	2.92+E08	-0.0144965	2.438406
Rayleigh	Optimistic	High	n/a	n/a	125,378	n/a	n/a	n/a	85446.18	312097.4	182695	71131.37	5.05+E09	0.9345519	3.78427

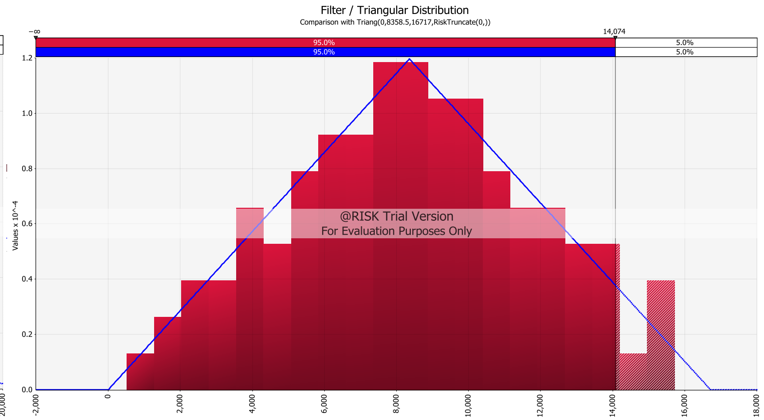


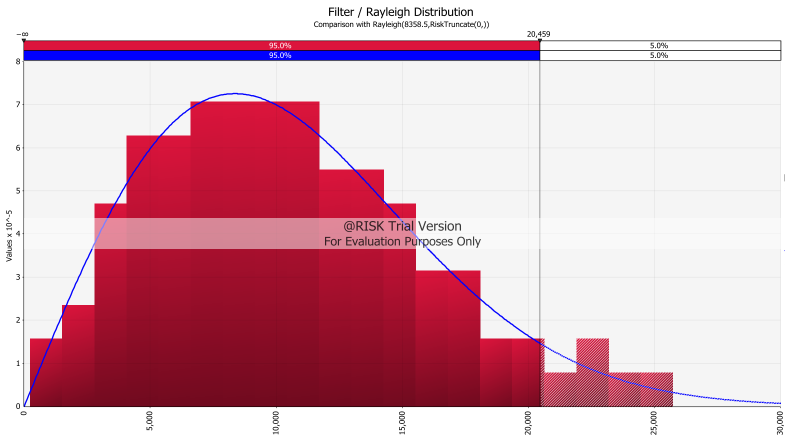




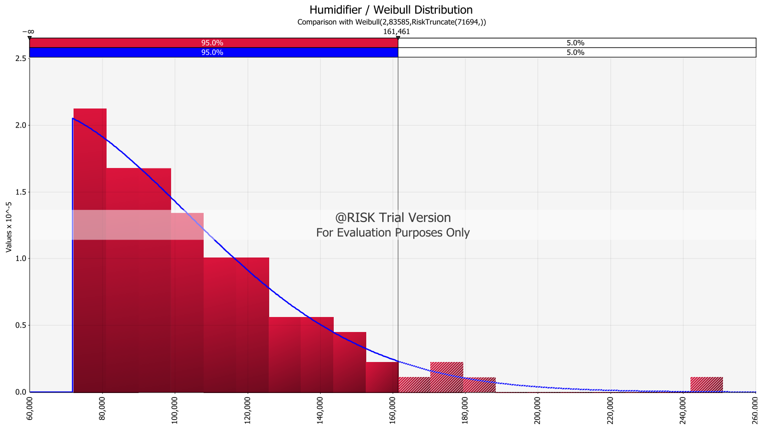
Distribution	Lifecycle Pseudonym	Risk Profile	Parameters						Min	Max (95% perc.)	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			y	α	β	Min life	Mean Life	Max Life							
Weibull	Conservative	Low	0	2	125,378	n/a	n/a	n/a	23170.57	212623.6	113691.8	55993.04	3.13+E09	0.6290312	3.005017
Triangular	Balanced	Medium	n/a	n/a	n/a	83,790	125,378	166,965	31142.78	193797.3	125381.9	43071.23	1.85+E09	0.01442449	2.480489
Rayleigh	Optimistic	High	n/a	n/a	125,378	n/a	n/a	n/a	25572.42	305118.2	159687.8	83368.15	6.95+E09	0.8778144	4.288121

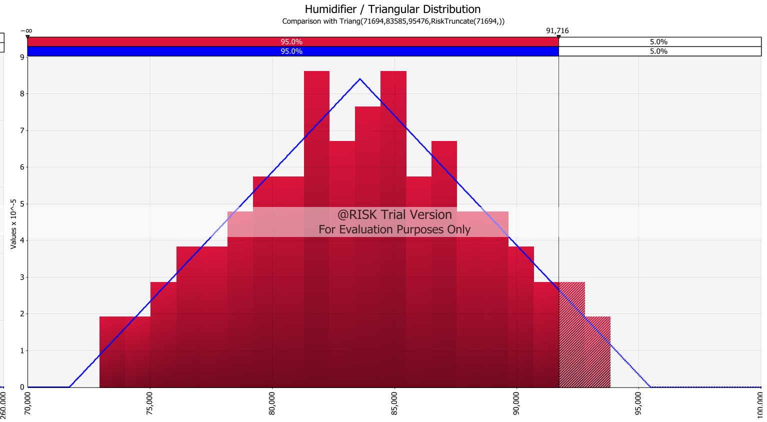


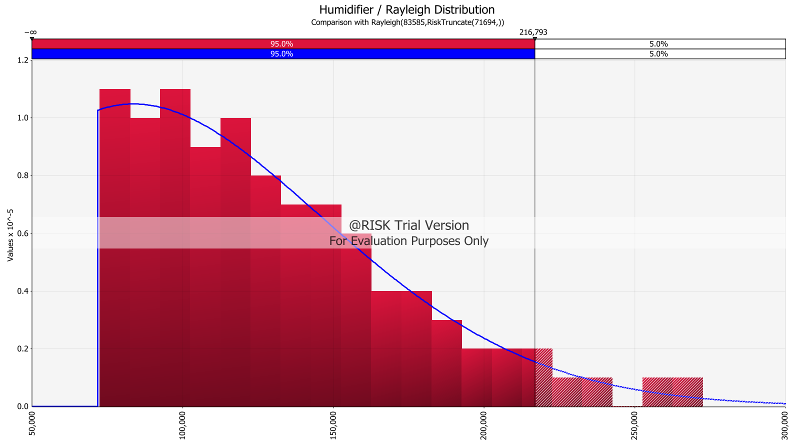




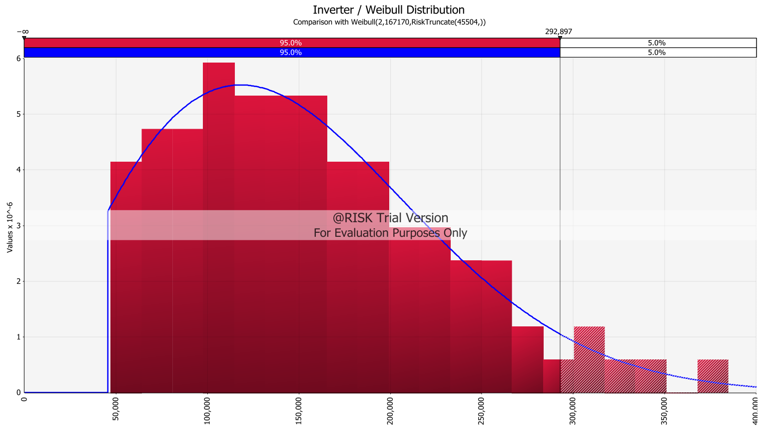
Distribution	Lifecycle Pseudonym	Risk Profile	Parameters						Min	Max (95% perc.)	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			y	α	β	Min life	Mean Life	Max Life							
Weibull	Conservative	Low	0	2	8,359	n/a	n/a	n/a	614.5117	14277.77	7400.841	3864.163	1.49+E07	0.5828252	3.020637
Triangular	Balanced	Medium	n/a	n/a	n/a	0	8,359	16,717	1104.096	13872.32	8366.558	3440.634	1.18+E07	0.02203558	2.439902
Rayleigh	Optimistic	High	n/a	n/a	8,359	n/a	n/a	n/a	257.7664	20373.91	10492.9	5537.84	3.06+E07	0.6178509	3.163889

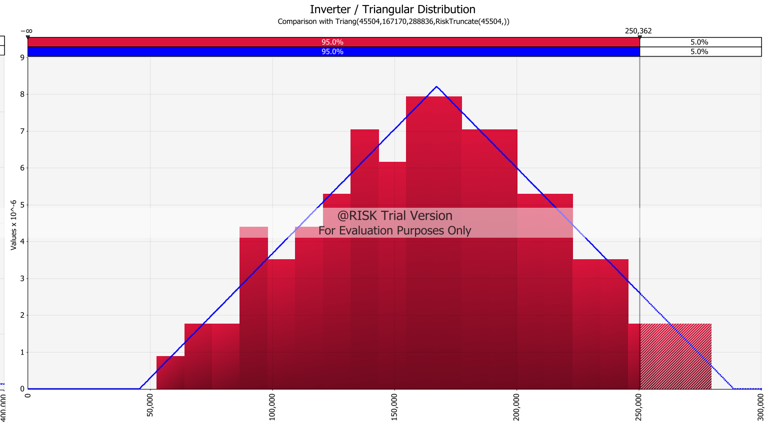


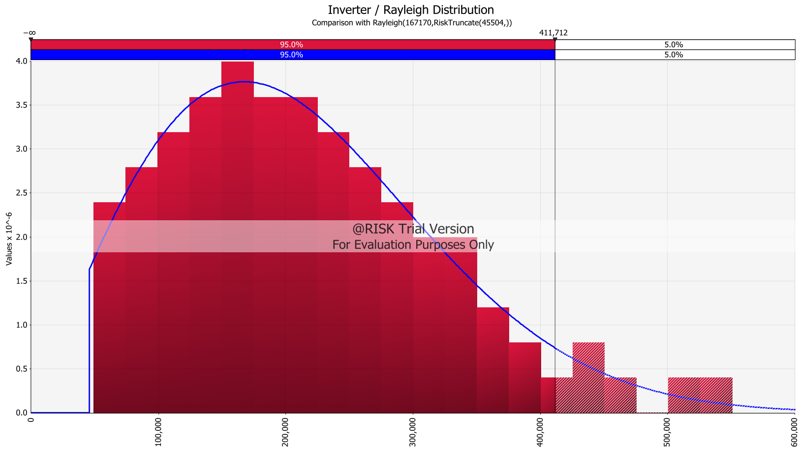




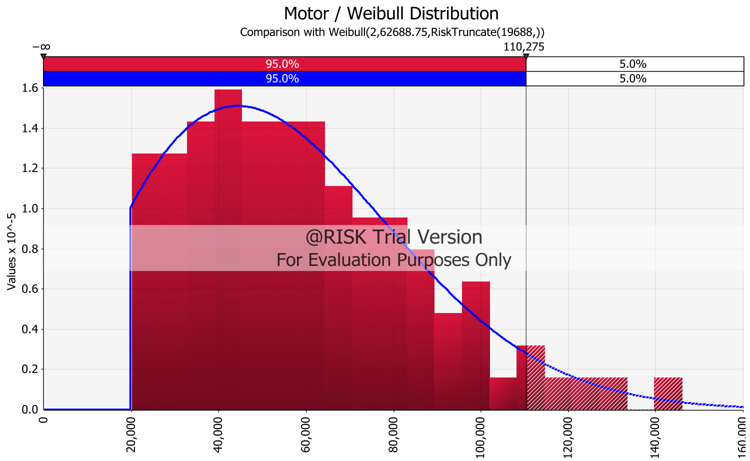
Distribution	Lifecycle Pseudonym	Risk Profile	Parameters						Min	Max (95% perc.)	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			γ	α	β	Min life	Mean Life	Max Life							
Weibull	Conservative	Low	0	3.5	83,585	n/a	n/a	n/a	72167.37	159172.8	106548.1	28271.8	7.99+E08	1.192743	4.495864
Triangular	Balanced	Medium	n/a	n/a	n/a	71,694	83,585	95,476	72214.47	91630.3	83575.78	4899.63	2.40+E07	-0.0236437	2.448101
Rayleigh	Optimistic	High	n/a	n/a	83,585	n/a	n/a	n/a	71848.16	213961.5	131679.5	48410.69	2.34+E09	1.673081	8.118417

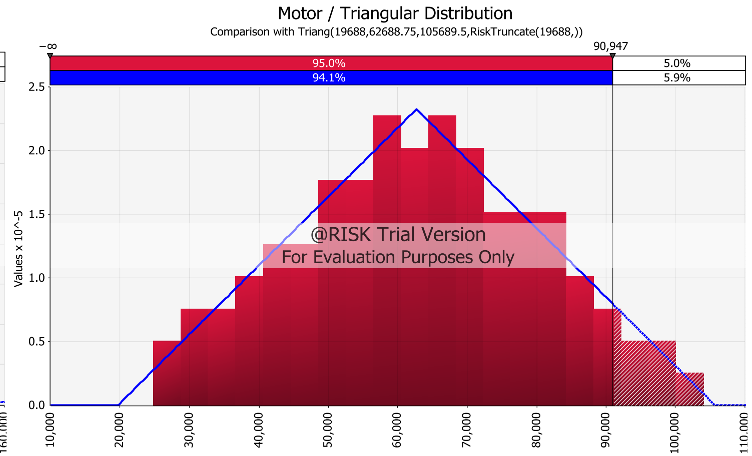


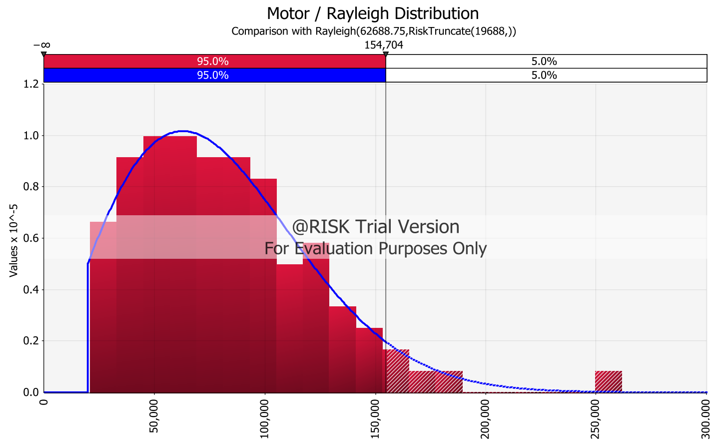




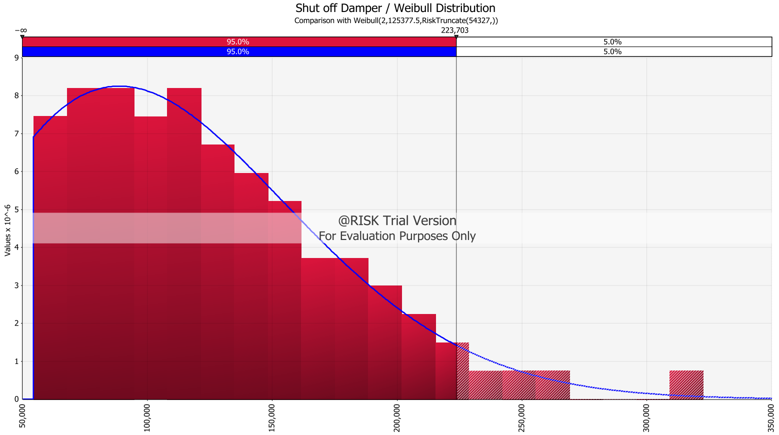
Distribution	Lifecycle Pseudonym	Risk Profile	Parameters						Min	Max (95% perc.)	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			y	α	β	Min life	Mean Life	Max Life							
Weibull	Conservative	Low	0	2	167,710	n/a	n/a	n/a	45570.29	291481.6	157103.2	72594.47	5.26+E09	0.7419856	3.267949
Triangular	Balanced	Medium	n/a	n/a	n/a	45,504	167,710	288,836	57089.5	249989.5	167220.3	49709.81	2.47+E09	-0.0024521	2.403553
Rayleigh	Optimistic	High	n/a	n/a	167,710	n/a	n/a	n/a	47630.23	400204.3	216396.7	106728.2	1.13+E10	0.7509672	3.443611

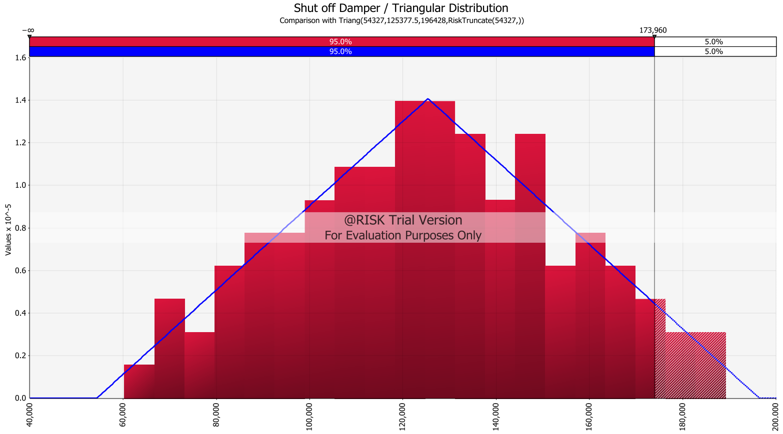


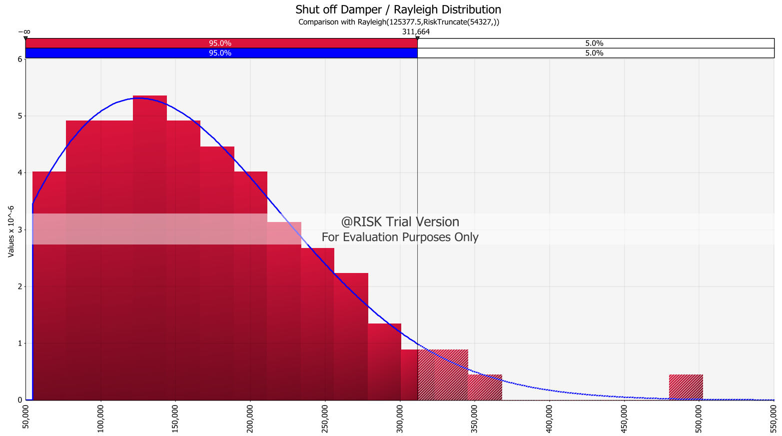




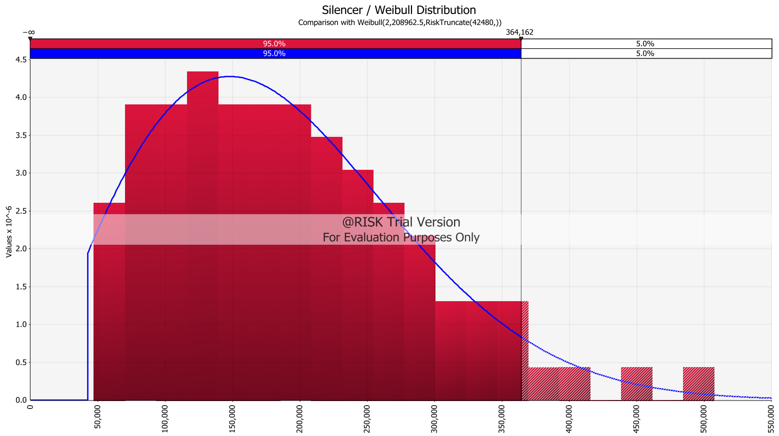
Distribution	Lifecycle Pseudonym	Risk Profile	Parameters						Min	Max (95% perc.)	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			y	α	β	Min life	Mean Life	Max Life							
Weibull	Conservative	Low	0	2	62,689	n/a	n/a	n/a	20,184	109,594	59960.83	26887.67	7.22E+08	0.7810072	3.328786
Triangular	Balanced	Medium	n/a	n/a	n/a	19,688	62,689	105,689	24,767	90,947	62721.66	17761.05	3.15E+08	0.0188723	2.466686
Rayleigh	Optimistic	High	n/a	n/a	62,689	n/a	n/a	n/a	20,798	150,982	82270.14	41216.98	1.69E+09	1.123652	5.488101

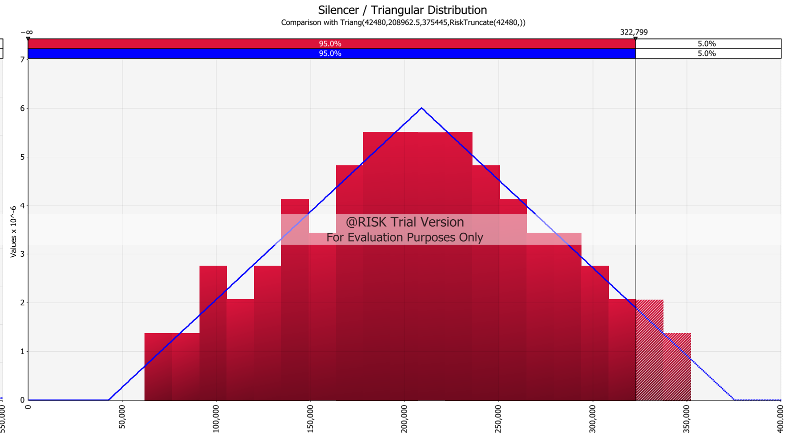


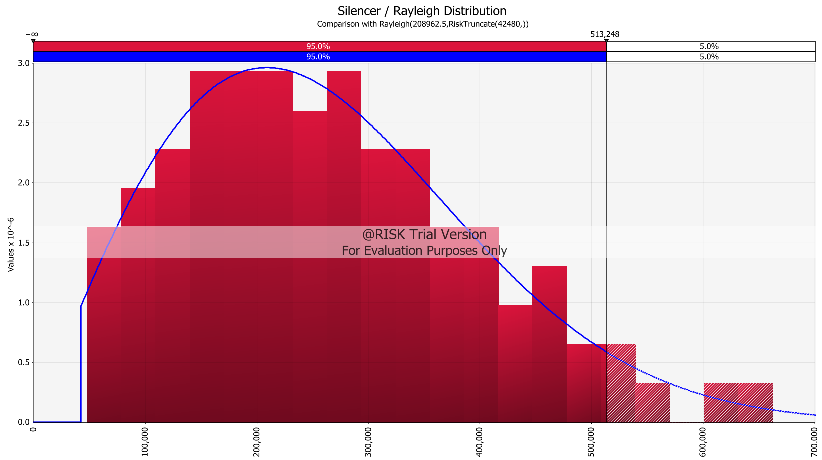




Distribution	Lifecycle Pseudonym	Risk Profile	Parameters						Min	Max (95% perc.)	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			y	α	β	Min life	Mean Life	Max Life							
Weibull	Conservative	Low	0	2	125,378	n/a	n/a	n/a	55483.51	221989.3	126845.9	51560.59	2.65+E09	0.8926715	3.543728
Triangular	Balanced	Medium	n/a	n/a	n/a	54,327	125,378	231,067	60332.12	172840.8	125433.9	29303.84	8.58+E08	0.02257476	2.465358
Rayleigh	Optimistic	High	n/a	n/a	125,378	n/a	n/a	n/a	56555.16	305001.4	168816.5	76134.58	5.79+E09	0.7899754	3.458869







Distribution	Lifecycle Pseudonym	Risk Profile	Parameters						Min	Max (95% perc.)	Mean	Standard Deviation	Variance	Skewness	Kurtosis
			y	α	β	Min life	Mean Life	Max Life							
Weibull	Conservative	Low	0	2	208,963	n/a	n/a	n/a	44240.91	363593	192041.5	94709.92	8.96+E09	0.7854061	3.582381
Triangular	Balanced	Medium	n/a	n/a	n/a	42,480	208,963	231,067	48410.7	322002.8	208769.8	68430.72	4.68+E09	-0.0441807	2.453372
Rayleigh	Optimistic	High	n/a	n/a	208,963	n/a	n/a	n/a	47809	502706.2	266252.5	132994.3	1.76+E10	0.6147358	3.015522

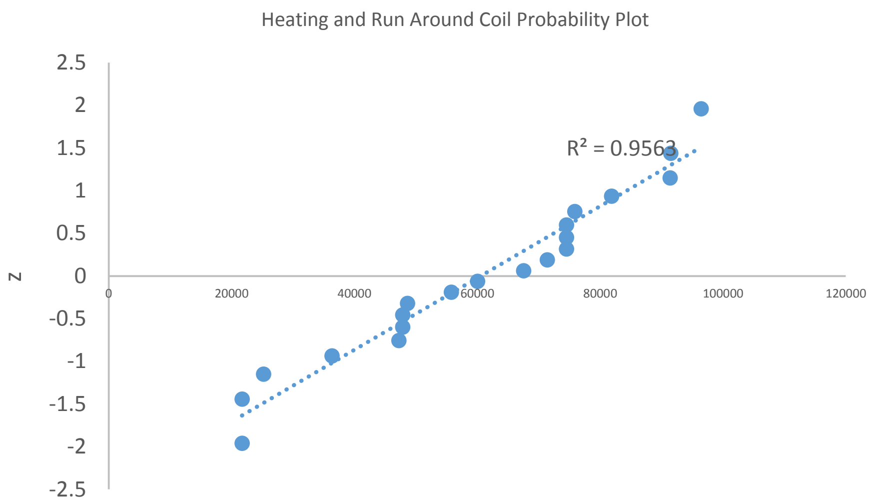
Name	Cooling & Frost Coil / Weibull Distribution	Heating & Run Around Coil / Weibull Distribution	Control Panel / Weibull Distribution	Fan (Supply and Extract) / Weibull Distribution	Filter / Weibull Distribution	Humidifier / Weibull Distribution	Inverter / Weibull Distribution	Motor / Weibull Distribution	Shut-off Damper / Weibull Distribution	Silencer / Weibull Distribution
Description	RiskWeibull(S61,T61,RiskTruncate(Y61))	RiskWeibull(S63,T63,RiskTruncate(Y63))	RiskWeibull(S66,T66,RiskTruncate(Y66))	RiskWeibull(S67,T67,RiskTruncate(Y67))	RiskWeibull(S71,T71,RiskTruncate(Y71))	RiskWeibull(S74,T74,RiskTruncate(Y74))	RiskWeibull(S75,T75,RiskTruncate(Y75))	RiskWeibull(S77,T77,RiskTruncate(Y77))	RiskWeibull(S79,T79,RiskTruncate(Y79))	RiskWeibull(S80,T80,RiskTruncate(Y80))
Cell	CDFs!U61	CDFs!U63	CDFs!U66	CDFs!U67	CDFs!U71	CDFs!U74	CDFs!U75	CDFs!U77	CDFs!U79	CDFs!U80
Minimum	12509.26	21769.73	83834.79	23577.14	775.3091	72170.69	20184.33	22440.19	54982.5	44240.91
Maximum	271366.2	278463.3	176969.8	312951.3	19783.74	205424.1	145986.5	284580.2	274808.5	519796.3
Mean	111558.4	113999.1	121694.1	113907.3	7406.091	106540.7	59960.83	113368.7	126475.8	192041.5
Std Deviation	56915.29	56393.61	20967.02	57060.78	3884.358	28151.79	26887.67	56448.48	50507.28	94709.92
Variance	3239350000	3180239000	439616000	3255932000	15088240	792523500	722946700	3186431000	2550985000	8969969000
Skewness	0.5502582	0.6401111	0.3037759	0.7529846	0.6164537	1.13725	0.7810072	0.6417186	0.7859874	0.7854061
Kurtosis	2.850277	2.996772	2.533443	3.552671	3.159291	4.155419	3.328786	3.070033	3.119716	3.582381
Errors	0	0	0	0	0	0	0	0	0	0
Mode	90624.73	105778.6	125544.6	123981.5	4843.73	72593.21	51274.91	92503.63	60429.02	128132.9
5% Perc	29653.73	35359.79	88905.54	33987.99	1785.873	73662.96	23545.44	33662.5	59989.68	60579.37
10% Perc	41374.72	45275.66	94035.18	44422.51	2646.562	76225.98	28092.64	44525.04	67079.56	78691.87
15% Perc	51627.07	53360.33	98220.85	54426.71	3349.349	78806.63	31594.37	53659.98	73329.71	92226.84
20% Perc	58705.41	62011.95	101983.6	62164.3	3946.755	81678.88	35016.03	60865.24	79428.84	106510.3
25% Perc	66715.84	69655.02	105052.1	69401.77	4412.47	84420.09	38843.77	69591.28	86048.7	118122.5
30% Perc	75252.16	77863.45	108385	76980.95	4907.57	87313.35	41948.43	76546.01	91947.29	129750.6
35% Perc	81978.55	83959.79	111568.1	83537.14	5438.764	89695.58	45339.49	84157.57	97882.81	141893.1
40% Perc	89811.52	91517.34	114435.5	91669.52	5884.9	92859.51	48661.09	91220.58	104406	153897
45% Perc	97412.21	98333.14	117723.4	98342.73	6444.27	96516.54	51810.29	98493.65	110021.6	165701.1
50% Perc	104620.4	105679.5	120663.8	105130.2	6925.438	99905.55	55521.04	105637.6	116866.6	177158.5
55% Perc	111557.1	112648.1	123251.2	113198.5	7425.376	103214.9	58916.41	112984.6	123414.5	190386.1
60% Perc	118983	121606.9	126007.7	120266.4	7958.789	107112.3	62813.3	120213.4	131408.3	204179.5
65% Perc	127431.5	128707.9	129628.5	129929.2	8498.076	111462.4	66891.98	128843.7	138041.4	216672.6
70% Perc	136558.8	138630.6	132546.2	137614.8	9165.991	116242.2	70655.48	137893.6	146585.2	232829.3
75% Perc	147102.5	148589	136039	147542	9762.782	120702	75904.97	148377	156101.1	246916.3
80% Perc	158665.2	160462.2	139727.4	158988.5	10588.76	127588.5	81292.51	158153.1	166263.4	265345.6
85% Perc	171895.9	171755.1	144044.5	173074.9	11376.51	134332.3	87536.66	173015	178718.7	289006.3
90% Perc	187220.4	190185.3	149029.3	190677	12656.61	144195	96625.23	190391.2	195906.5	318133.2
95% Perc	214140.7	217008.1	155706.9	214431	14407.12	159121.2	109594.4	211595.3	222901.4	363593

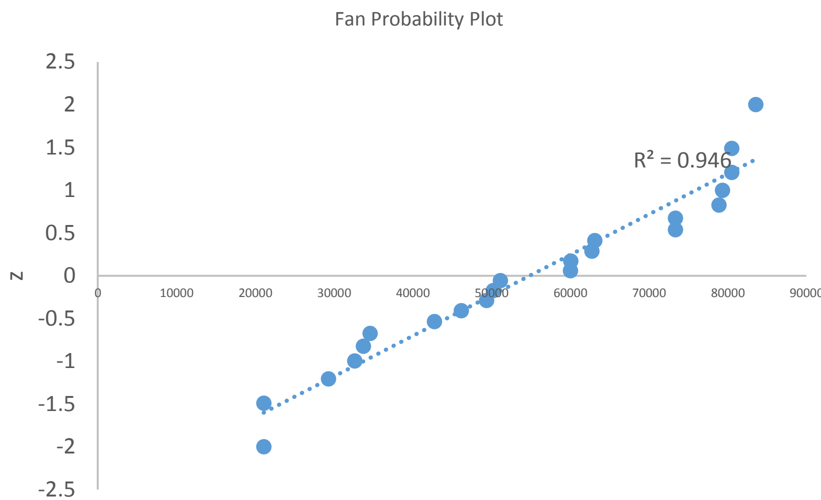
.

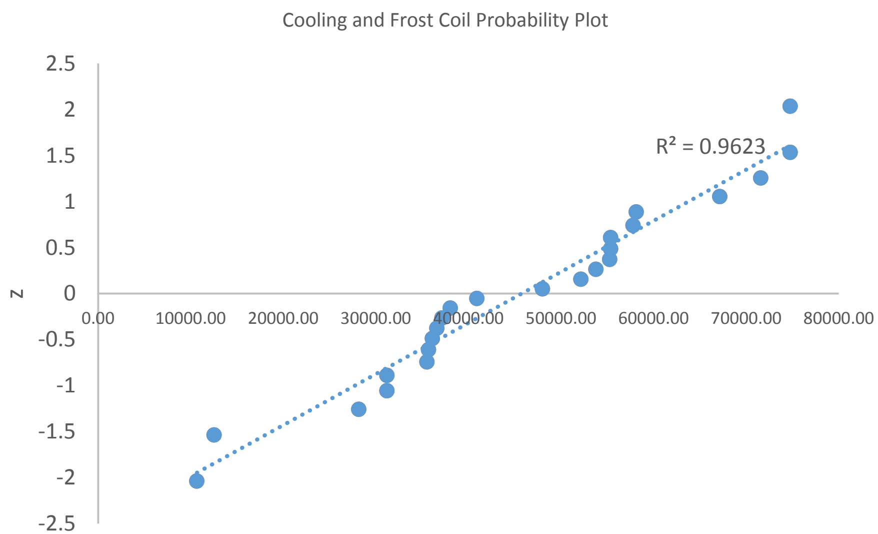
Name	Cooling & Frost Coil / Triangular Distribution	Heating & Run Around Coil / Triangular Distribution	Control Panel / Triangular Distribution	Fan (Supply and Extract) / Triangular Distribution	Filter / Triangular Distribution	Humidifier / Triangular Distribution	Inverter / Triangular Distribution	Motor / Triangular Distribution	Shut-off Damper / Triangular Distribution	Silencer / Triangular Distribution
Description	RiskTriang(O35,P35,Q35,RiskTruncate(Y35))	RiskTriang(O37,P37,Q37,RiskTruncate(Y37))	RiskTriang(O40,P40,Q40,RiskTruncate(Y40))	RiskTriang(O41,P41,Q41,RiskTruncate(Y41))	RiskTriang(O45,P45,Q45,RiskTruncate(Y45))	RiskTriang(O48,P48,Q48,RiskTruncate(Y48))	RiskTriang(O49,P49,Q49,RiskTruncate(Y49))	RiskTriang(O51,P51,Q51,RiskTruncate(Y51))	RiskTriang(O53,P53,Q53,RiskTruncate(Y53))	RiskTriang(O54,P54,Q54,RiskTruncate(Y54))
Minimum	22757.03	35639.62	88676.74	26274.65	987.6715	73183.31	62287.34	24767.43	63045.21	48410.7
Maximum	227916	216594.3	162263.2	215458.4	16171.13	94282.71	280378.9	104038.5	189771	354362.8
Mean	125352	125374.5	125419.8	125202.8	8366.591	83575.22	167254	62721.66	125369.6	208769.8
Std Deviation	47014.78	42314.29	17072.03	42838.74	3437.166	4866.655	49937.96	17761.05	29110.26	68430.72
Variance	2210390000	1790499000	291454000	1835157000	11814110	23684330	2493800000	315455000	847407100	4682763000
Skewness	-0.00711356	0.003358453	0.01400448	-0.02699728	0.02120776	0.002395069	0.023139	0.01887232	0.01462102	-0.04418078
Kurtosis	2.422147	2.392426	2.413701	2.426528	2.434053	2.405579	2.420327	2.466686	2.401568	2.453372
Errors	0	0	0	0	0	0	0	0	0	0
Mode	117624.2	134662.2	131853.7	114754.3	8807.962	83519.13	158988.8	61202.02	125136.8	186896.2
5% Perc	45764.93	53175.18	96787.12	53102.17	2460.399	75231.63	80060.59	32550.74	76228.41	90679.76
10% Perc	61955.46	67366.27	101778.8	67692.93	3723.974	76739.88	99377.97	38222.35	85292.07	116500.9
15% Perc	73450.09	77968.6	106103.9	77221.41	4446.806	78029.66	111015.1	42546.5	92311.23	133641.6
20% Perc	82010.91	87073.32	109879.4	85759.43	5203.435	79086.16	121943.9	46421.45	99037.62	145695.9
25% Perc	91518.33	94199.8	112956.4	93776	5879.538	79968.1	130469.9	49606.91	103595.9	159078.4
30% Perc	98878.13	101930.4	115819.9	100993.2	6395.425	80822.72	139203.7	52699.08	108554.5	170707.7
35% Perc	105654.2	108104.7	118311.6	107545.7	6939.117	81539	147039.8	55369.56	113465.1	180532.9
40% Perc	112435.8	113334.7	120536.1	114041.7	7402.967	82197.35	154051.9	58006.29	117171.6	190534.6
45% Perc	118373.9	119537.5	122953.2	119572.4	7922.442	82960.15	160206	60381.29	121159.7	199758.2
50% Perc	125156.5	125017.8	125151.2	124880.9	8309.5	83486.6	167086.7	62306.23	125278.4	208552.2
55% Perc	130457.6	130509.7	127278.1	129908.5	8755.034	84117.81	173094.6	64705.78	128654.9	215857.9
60% Perc	136925.7	135264.3	129460.2	135461.5	9237.242	84812.4	179822.8	67223.27	132416.2	226056.7
65% Perc	143348.5	141311.3	131729.3	141328.3	9659.241	85507.02	186159.4	69248.56	136598.3	235460.9
70% Perc	150751.3	147496.2	134729.6	148656	10232.93	86226.01	193654.8	72305.66	140721.3	245724.7
75% Perc	158423.2	154402.5	137016.8	154782.5	10731.17	86934.18	202231.7	75261.63	145196	257196.1
80% Perc	166244.8	162504.6	140538.7	162987.8	11318.93	87887.11	210775.8	78321.02	151138.4	268028.3
85% Perc	175525.5	171034.6	144061.4	170695.5	12121.49	88949.81	221933.8	81491.8	157428.9	283192.2
90% Perc	188276.4	182339.5	148182.1	182288.5	12890.5	89901.67	233617.9	85970.13	163324.9	300324.9
95% Perc	201049.4	195389.3	153813.2	196319.1	14037.67	91517.92	248246.9	90947.2	172765.2	322002.8

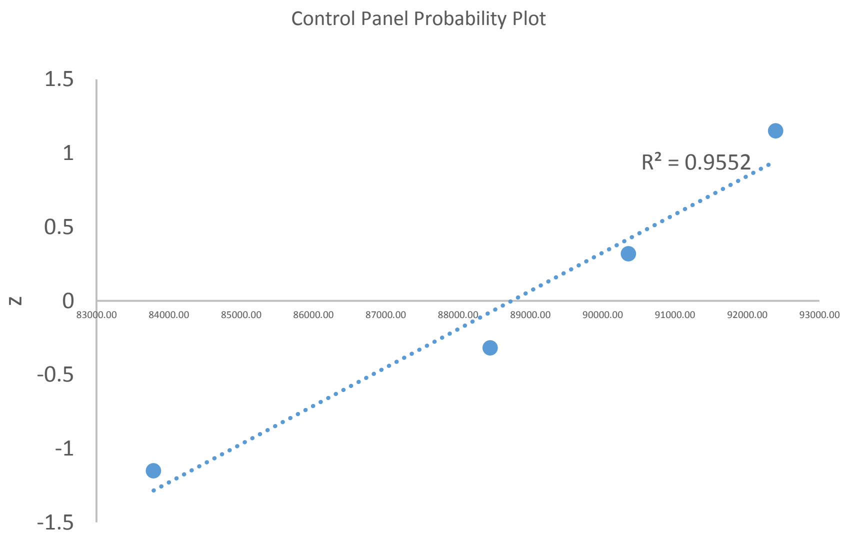
Name	Cooling & Frost Coil / Rayleigh Distribution	Heating & Run Around Coil / Rayleigh Distribution	Control Panel / Rayleigh Distribution	Fan (Supply and Extract) / Rayleigh Distribution	Filter / Rayleigh Distribution	Humidifier / Rayleigh Distribution	Inverter / Rayleigh Distribution	Motor / Rayleigh Distribution	Shut-off Damper / Rayleigh Distribution	Silencer / Rayleigh Distribution
Description	RiskRayleigh(V86,RiskTruncate(Y86))	RiskRayleigh(V89,RiskTruncate(Y89))	RiskRayleigh(V92,RiskTruncate(Y92))	RiskRayleigh(V93,RiskTruncate(Y93))	RiskRayleigh(V97,RiskTruncate(Y97))	RiskRayleigh(V100, RiskTruncate(Y100))	RiskRayleigh(V101, RiskTruncate(Y101))	RiskRayleigh(V103, RiskTruncate(Y103))	RiskRayleigh(V105, RiskTruncate(Y105))	RiskRayleigh(V106, RiskTruncate(Y106))
Cell	CDFs!W86	CDFs!W89	CDFs!W92	CDFs!W93	CDFs!W97	CDFs!W100	CDFs!W101	CDFs!W103	CDFs!W105	CDFs!W106
Minimum	19619.17	28036.88	84270.44	23415.87	696.0426	72422.16	48709.85	20798.47	54516.7	47809
Maximum	424039.9	391814	402669.2	411382.5	26051.49	275330.3	510586.1	261608.6	400383.3	662345.6
Mean	157473.2	159137.3	182597.8	158920.7	10454.07	130759.3	215826.7	82270.14	168805.8	266252.5
Std Deviation	81973.79	80538.16	70612	80619.71	5461.36	44386.32	105006.8	41216.98	75719.4	132994.3
Variance	6719702000	6486395000	4986055000	6499537000	29826460	1970146000	11026430000	1698839000	5733428000	17687490000
Skewness	0.6486344	0.6082147	0.8395277	0.6233013	0.5507658	0.9640388	0.6475753	1.123652	0.7389185	0.6147358
Kurtosis	3.265059	2.960608	3.285249	3.096197	2.933978	3.653872	2.999654	5.488101	3.174883	3.015522
Errors	0	0	0	0	0	0	0	0	0	0
Mode	109668.1	161323.1	152530.9	104666.8	5986.337	78942.07	168398.1	79241.84	80156.05	166106.7
5% Perc	39999.01	42629.53	91297.96	42047.33	2603.228	76183.91	68470.97	27941.49	65991.48	75992.3
10% Perc	57821.3	60084.37	100915.3	58670.89	3783.346	80746.3	88232.45	33694.8	78719.68	101431.3
15% Perc	70368.85	73967.34	109673	73428.55	4761.339	86042.83	103322.3	40610.76	88074.52	123957.1
20% Perc	82522.03	84814.05	117442.4	84360.58	5548.632	89965.09	119560	45308.49	98759	143237.7
25% Perc	94758.88	95739.73	125695.5	96486.44	6311.299	95249.67	133426.9	50907.48	108045.4	164080
30% Perc	104742.6	106052.2	133424.2	106028	6973.228	100105.1	145816.5	55925.38	118945.5	181208.7
35% Perc	115619.5	117463	143363.2	116950.5	7709.961	105245	159689	60686.38	127357.2	198106.2
40% Perc	125981.4	128106.1	151490.7	127035.5	8404.305	110051	172525.1	65453.75	136647.6	212897.9
45% Perc	135846	137939.4	159041.6	138348.1	9052.971	115626.4	186150.2	70423.07	146315.3	232113.5
50% Perc	147018.8	148901.6	169156.5	148335.6	9796.749	120863.1	200048.2	75874.8	156378.6	246928.3
55% Perc	158085.1	159516.7	177825.5	159095.7	10490.37	127218.4	214514	81131.55	165971.3	263913
60% Perc	168288	171080.6	187503.7	170093.8	11162.98	133212	229863.3	86360.05	176911.5	284471.5
65% Perc	181774.9	181982	198885.4	182047.8	12056.88	140025.6	245547	92294.83	188431.8	302053.1
70% Perc	192647.4	193927.4	209502.2	194230.6	12814.46	147448.4	263115.5	99053.74	200712.9	325040.2
75% Perc	206210.1	207822.6	224444.9	208332.4	13852.6	156505.3	278490.8	104996.8	215204.3	349849.3
80% Perc	222587.9	225902	238099	223875.4	14799.54	166043.1	300750.8	113249.8	231391.7	371893.4
85% Perc	240595.6	242569.7	258064.2	245007.1	16064.34	176338.9	324002.6	122404.9	246678.6	406234.5
90% Perc	264198.9	264848	281680.5	267224.4	17843.62	192645.4	358940.3	133776.7	269509	449261.3
95% Perc	302367.9	305624.6	311686.8	300472.4	20162.84	215830	410413.5	150982.6	303823.2	502706.2

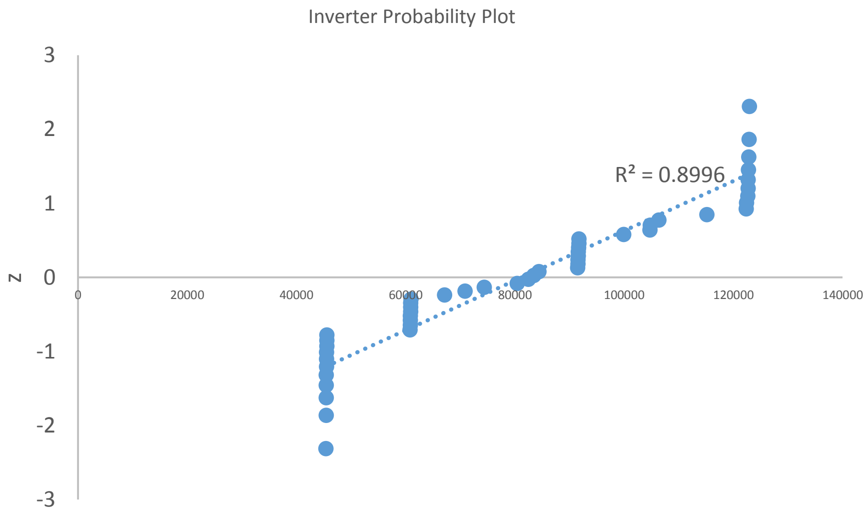
Appendix 16. Part Probability Plotting



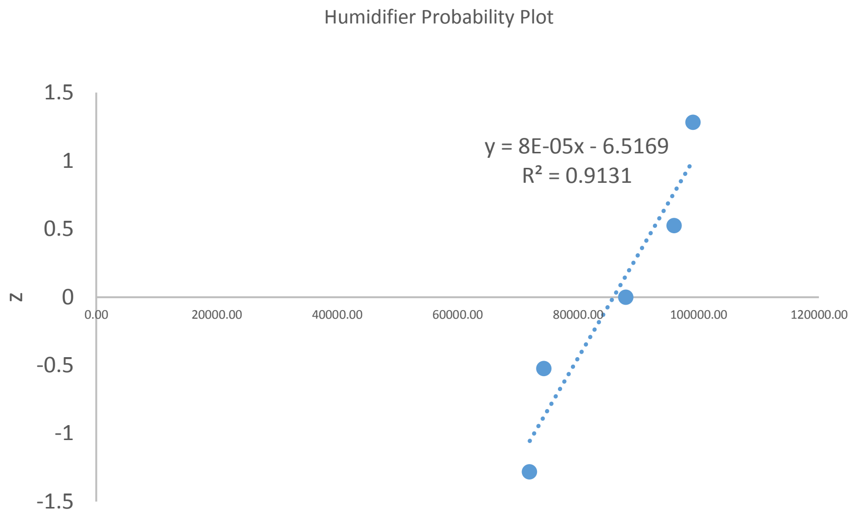




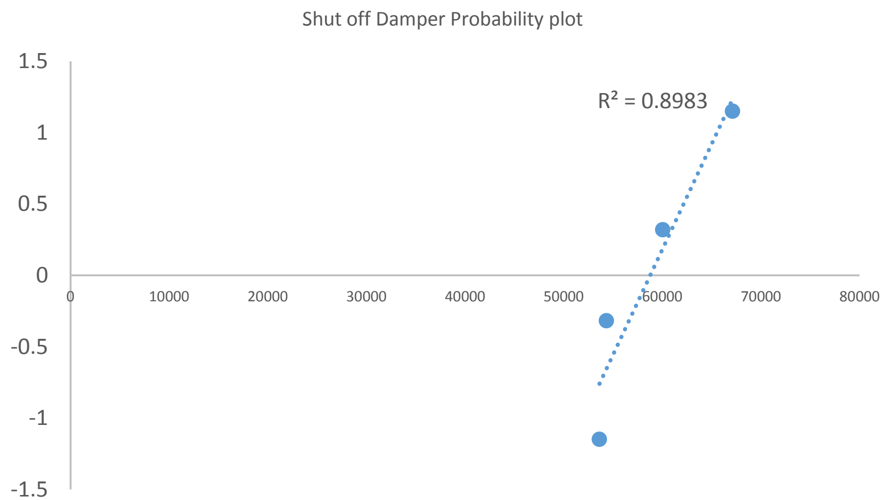




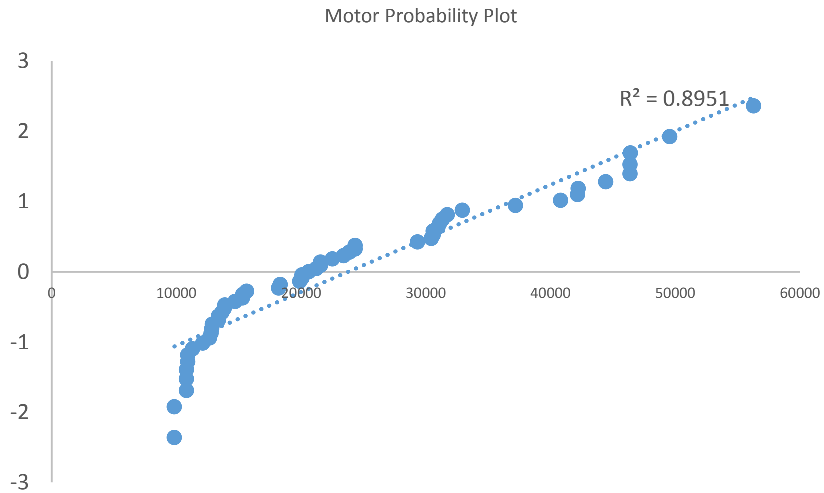
Inverter Probability Plot
R² = 0.8996
z
3
2
1
0
-1
-2
-3
0
20000
40000
60000
80000
100000
120000
140000



Humidifier Probability Plot
y = 8E-05x - 6.5169
R² = 0.9131
z
1.5
1
0.5
0
-0.5
-1
-1.5
0.00
20000.00
40000.00
60000.00
80000.00
100000.00
120000.00

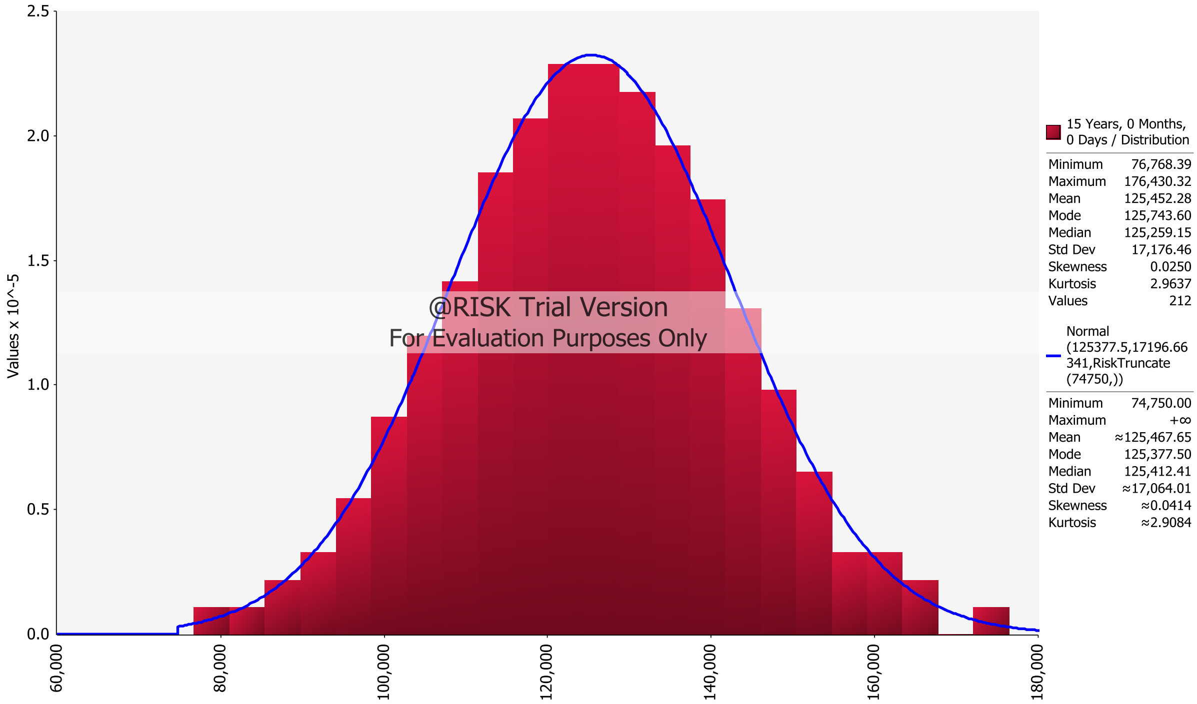


Shut off Damper Probability plot
R² = 0.8983
z
1.5
1
0.5
0
-0.5
-1
-1.5
0
10000
20000
30000
40000
50000
60000
70000
80000

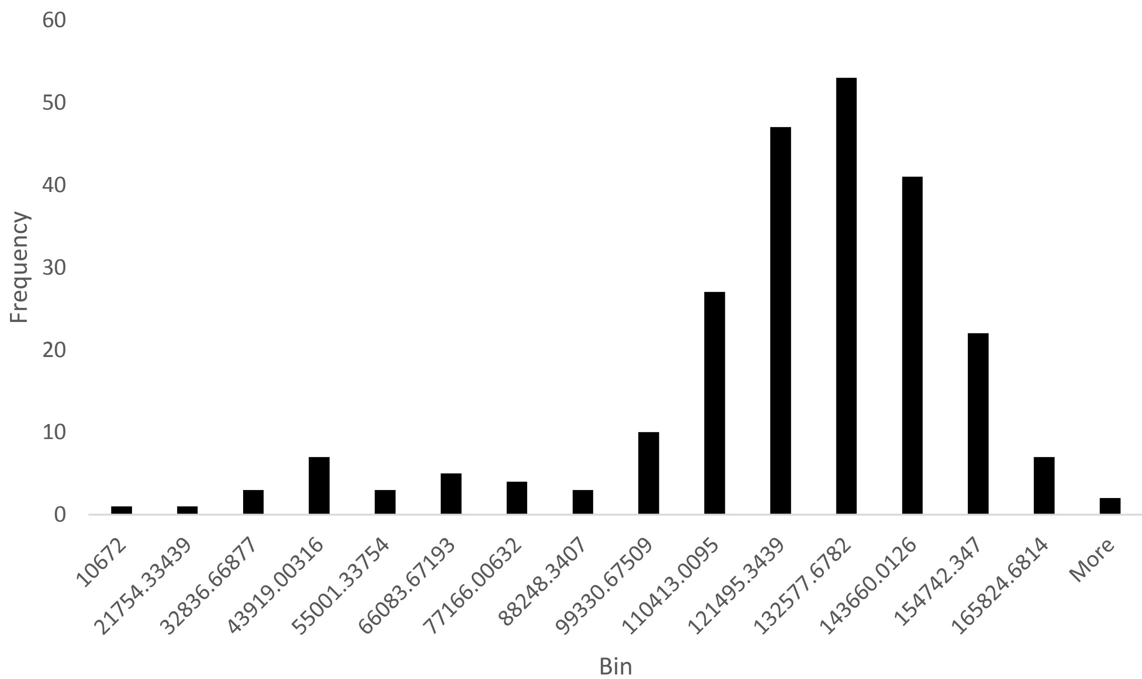


Motor Probability Plot
R² = 0.8951
3
2
1
0
-1
-2
-3
0
10000
20000
30000
40000
50000
60000

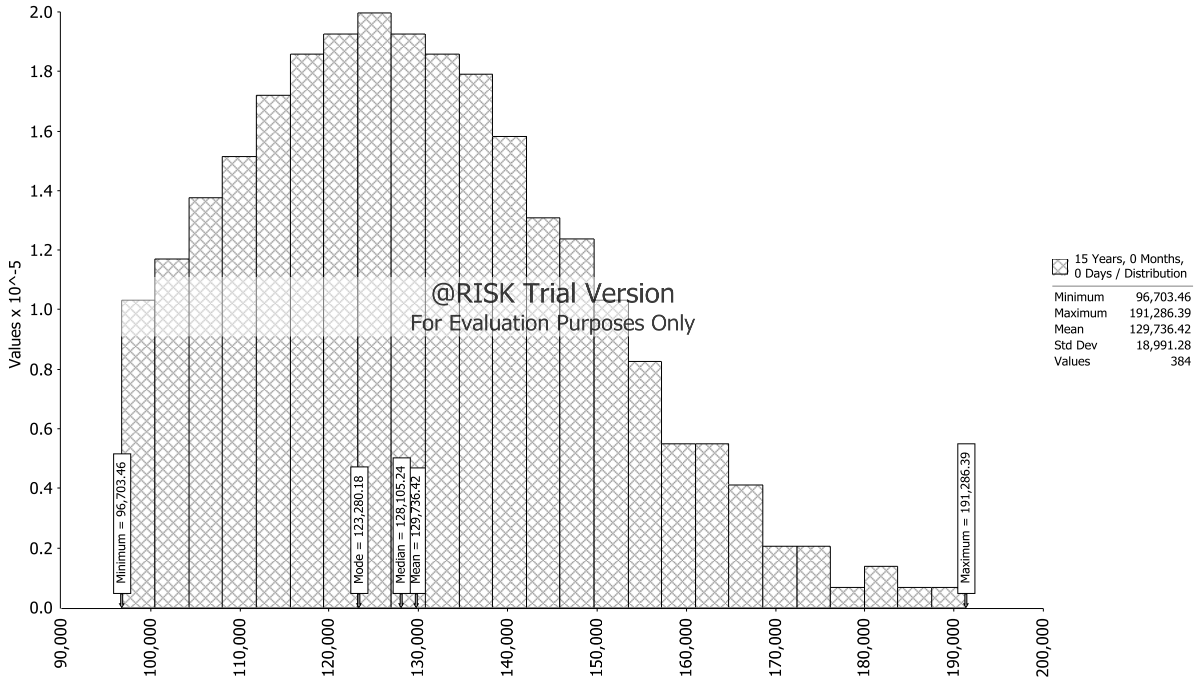
Appendix 17. CIBSE and HCP Part-Failure Histograms



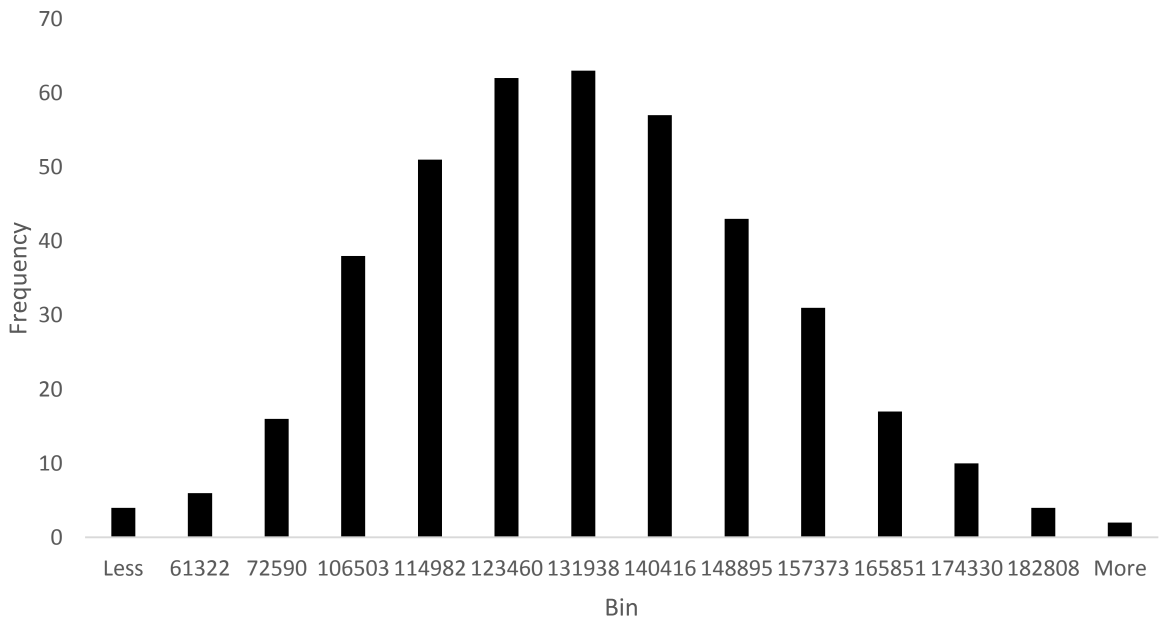
@risk Monte Carlo histogram (CIBSE only) and statistics – Cooling and frost coil



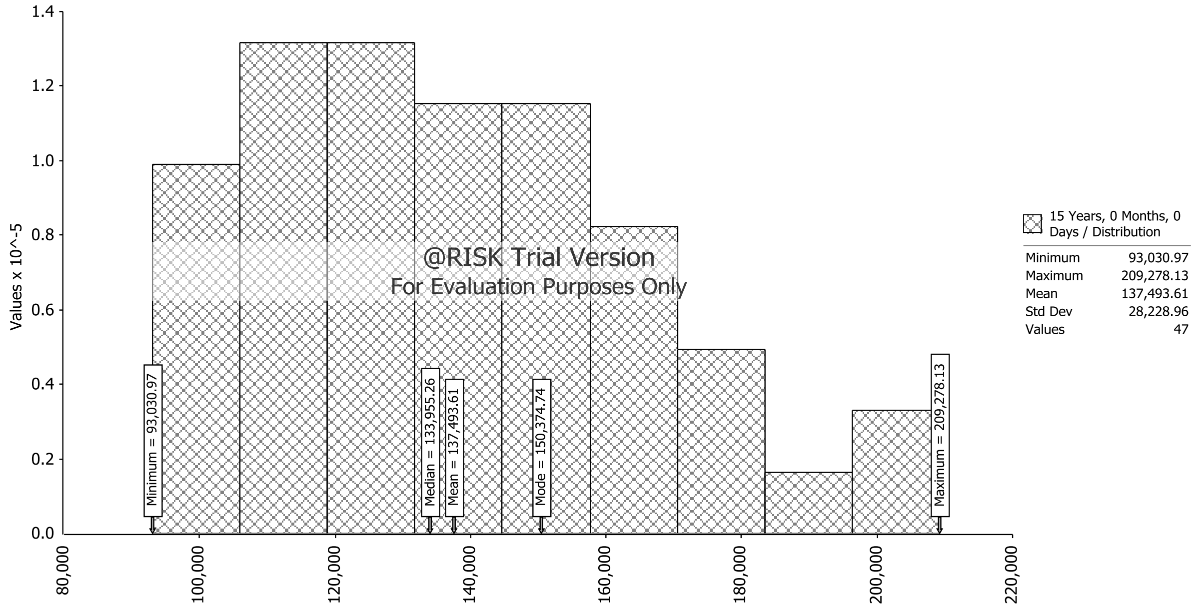
Cooling and Frost Coil Histogram (HCP & CIBSE)



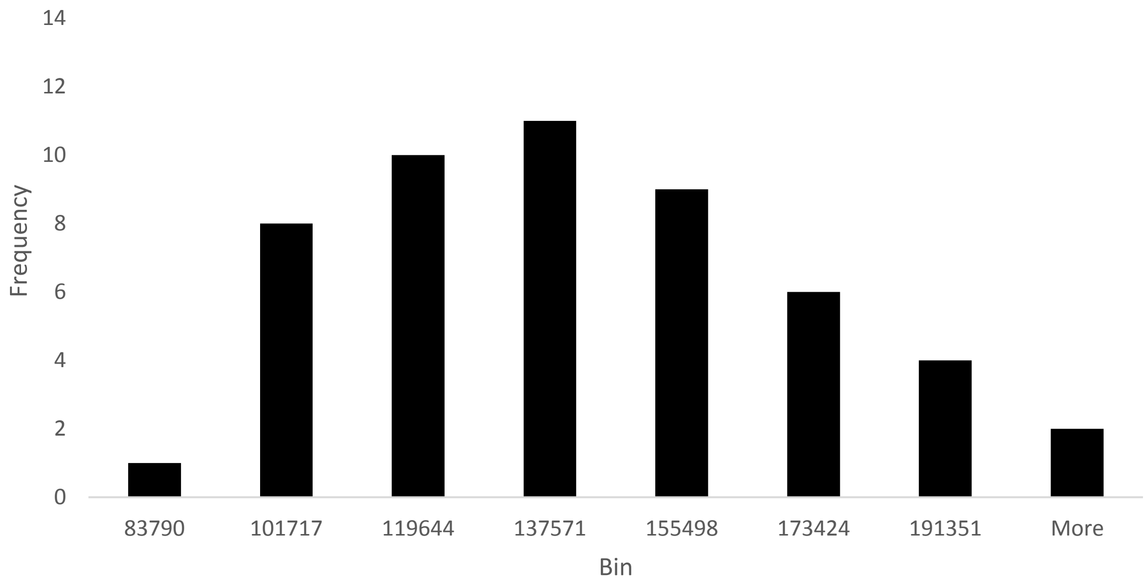
@risk Monte Carlo histogram (CIBSE only) and statistics -Heating and run around



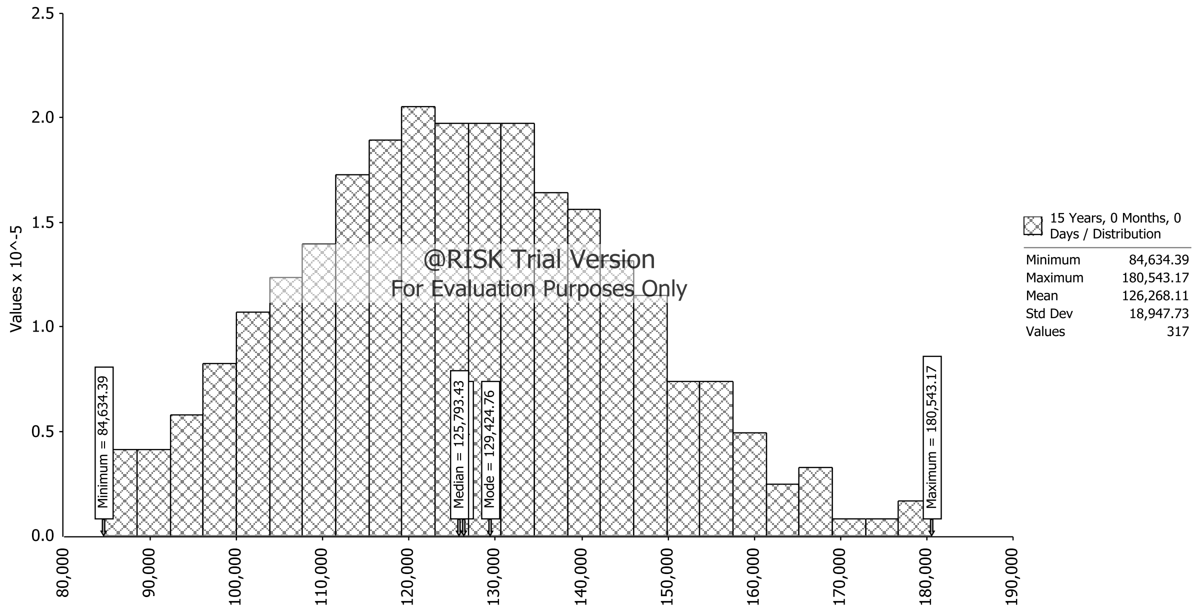
Heating and run around coil histogram (HCP & CIBSE)



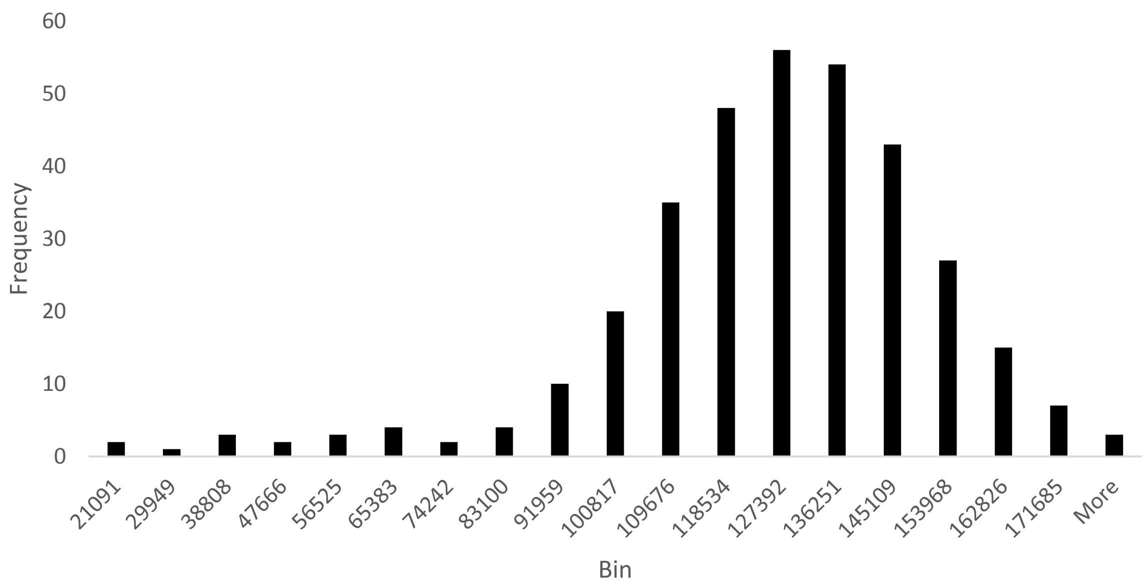
@risk Monte Carlo histogram (CIBSE only) and statistics – Control panel



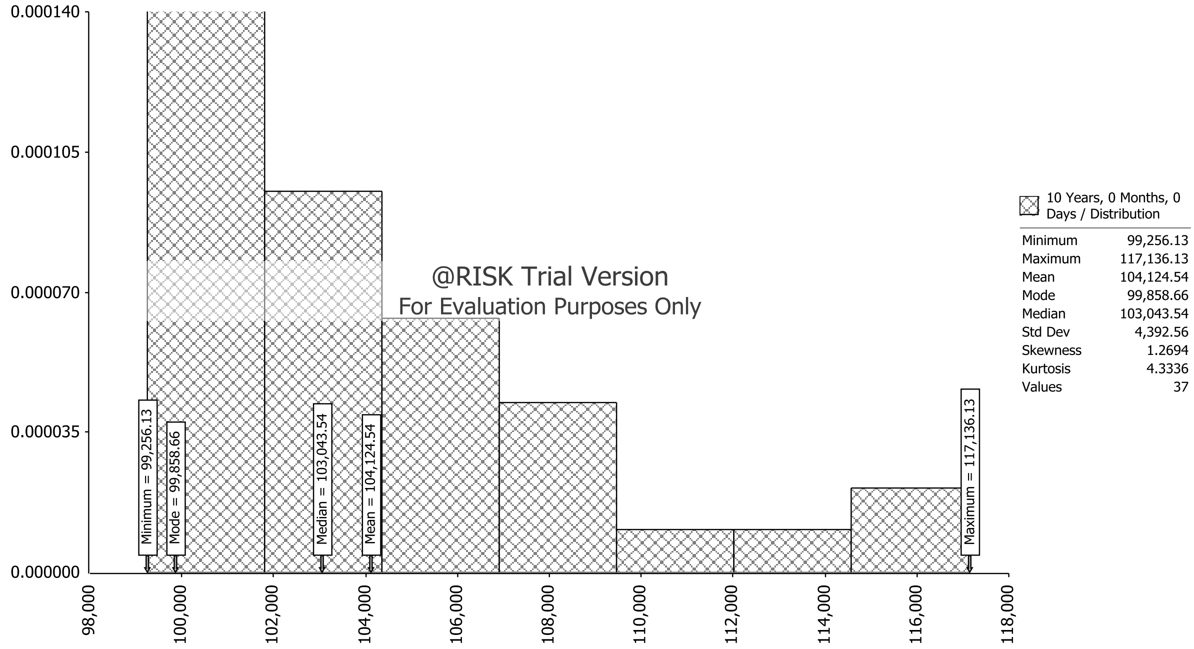
Control panel histogram (HCP & CIBSE)



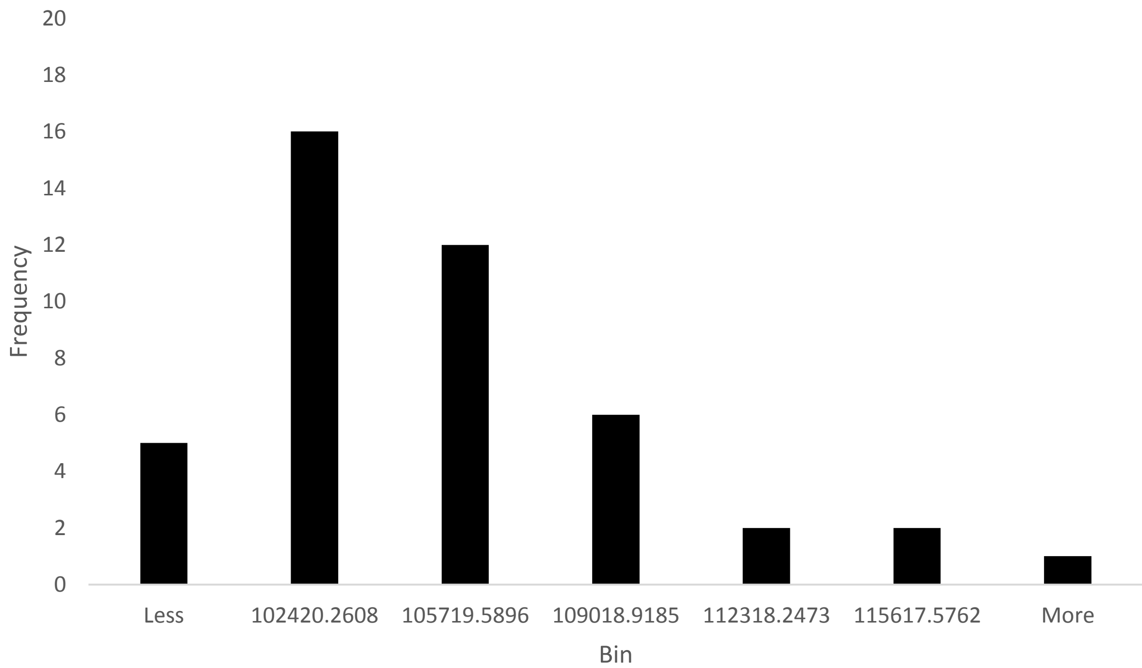
@risk Monte Carlo histogram (CIBSE only) and statistics – Fan (supply and extract)



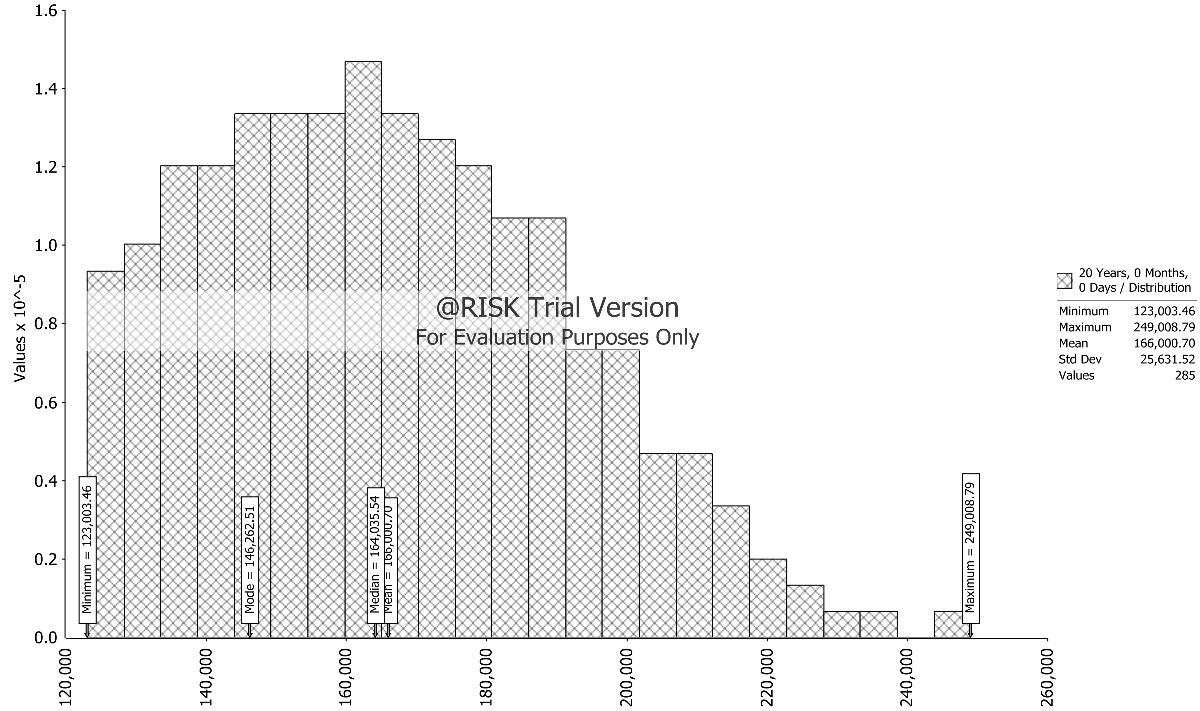
Fan (supply and extract) histogram (HCP & CIBSE)



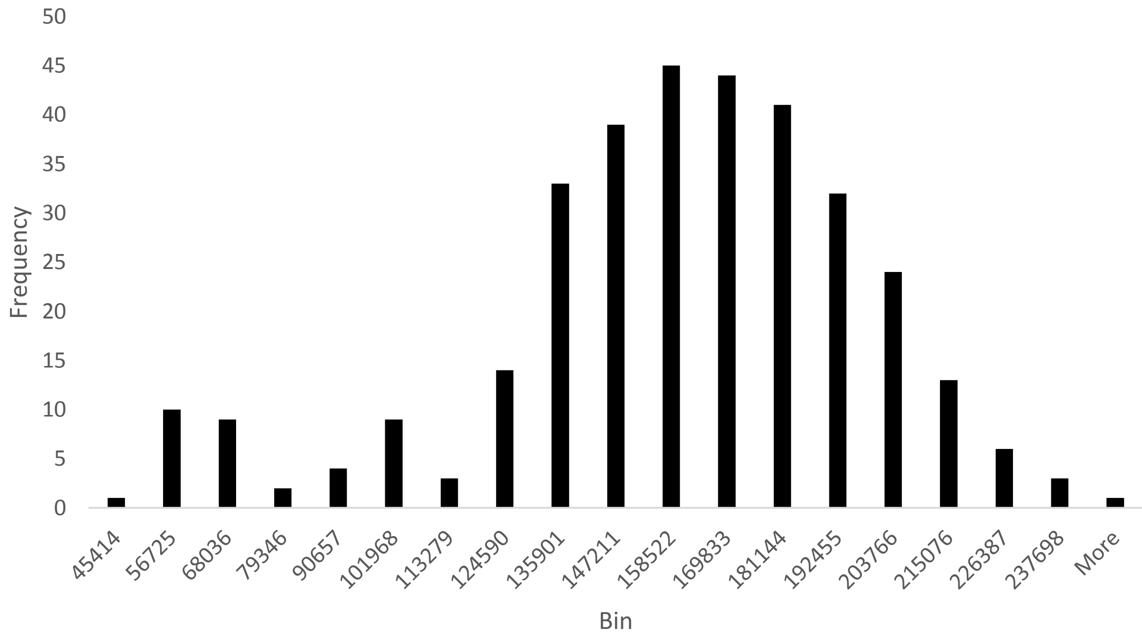
@risk Monte Carlo histogram and statistics (CIBSE only)



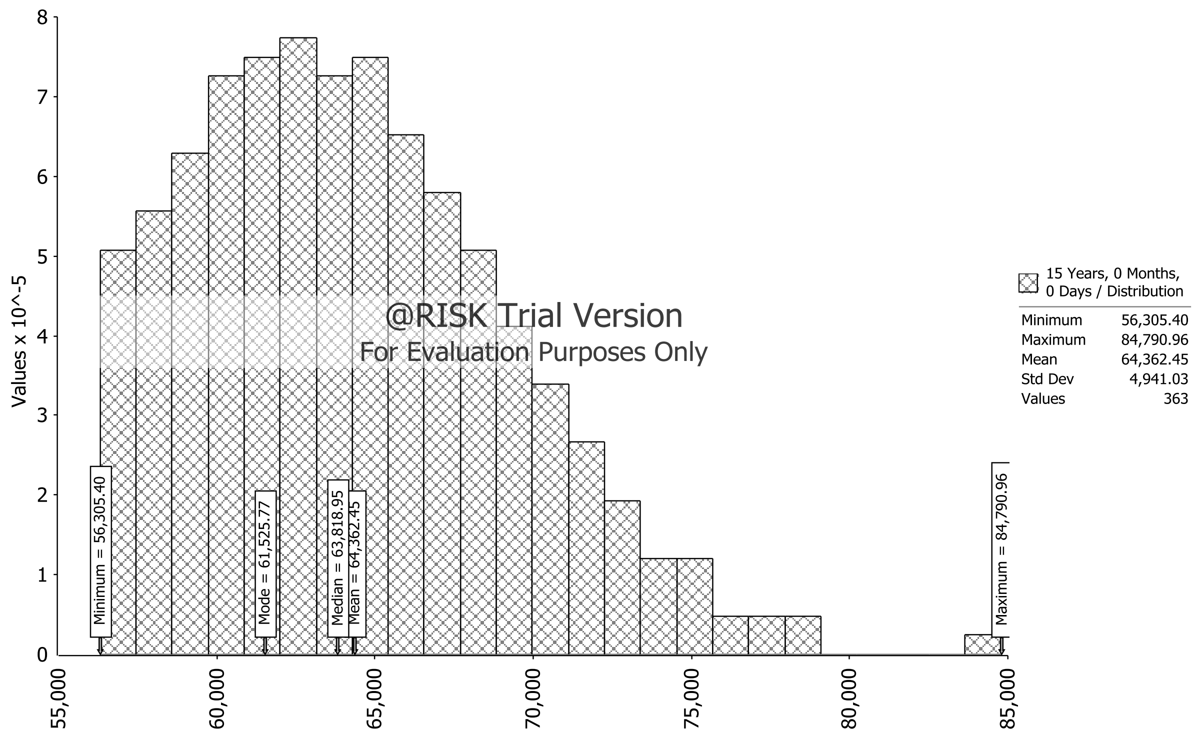
Humidifier Histogram (HCP & CIBSE)



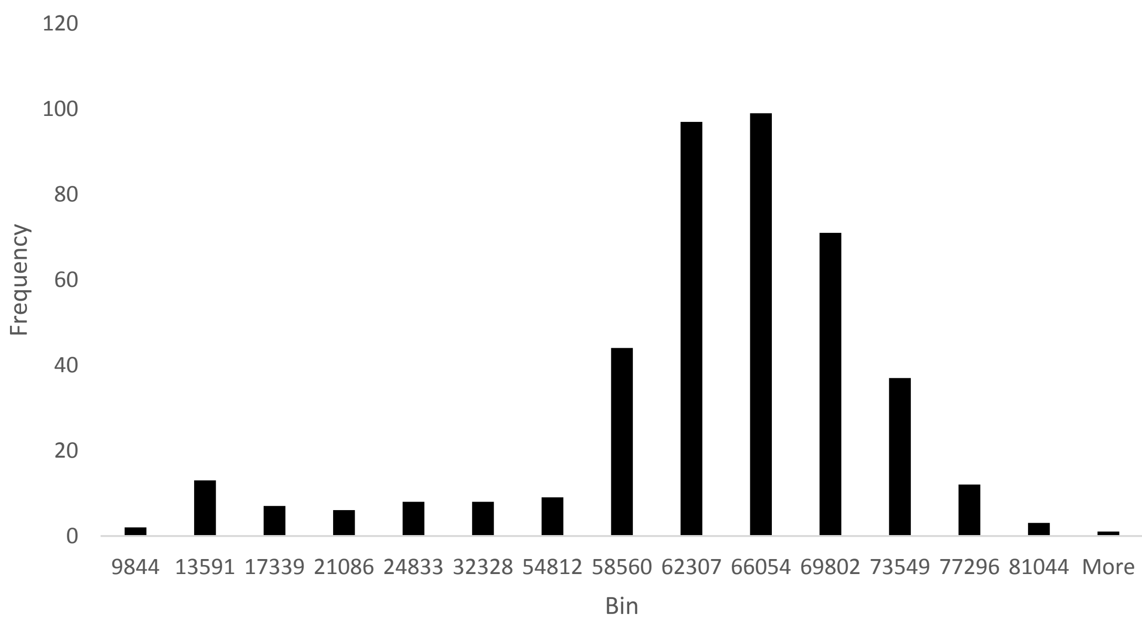
@risk Monte Carlo histogram and statistics (CIBSE only) – Inverter



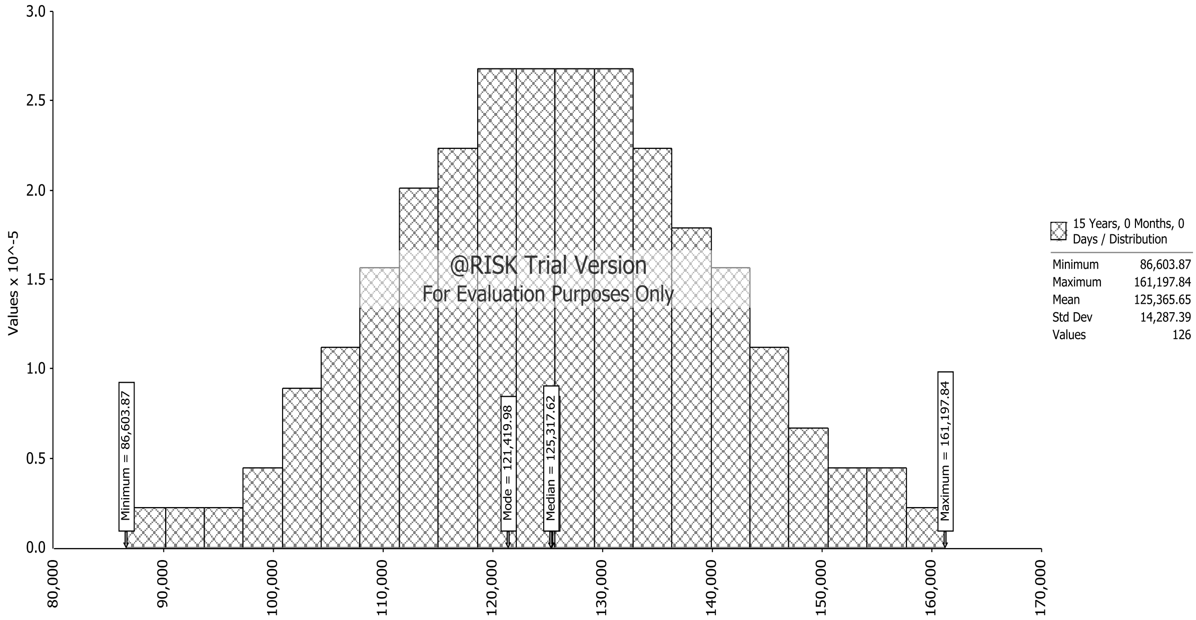
Inverter histogram (HCP & CIBSE)



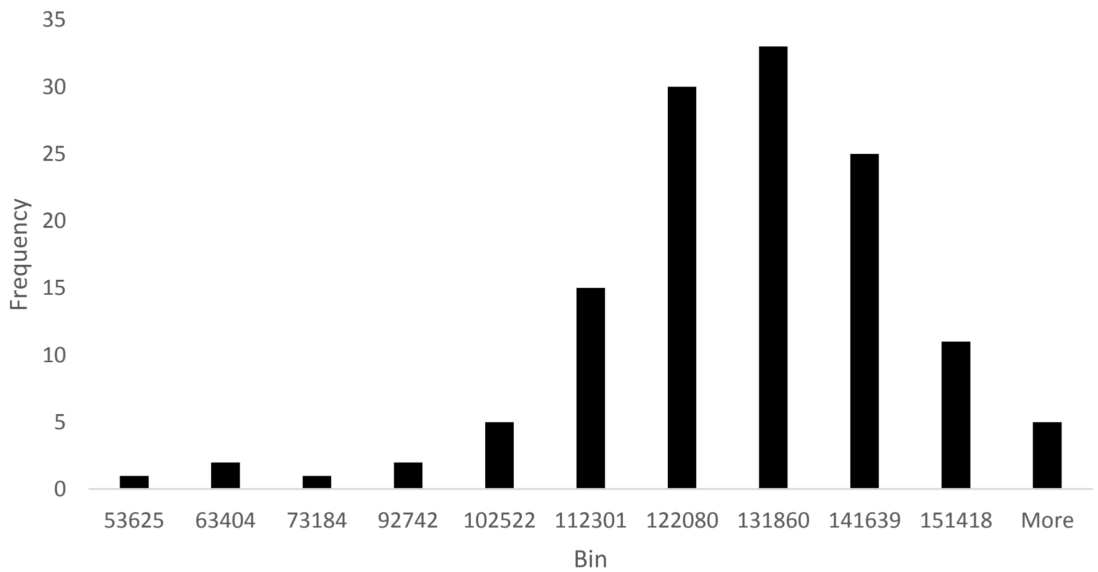
@risk Monte Carlo histogram and statistics (HCP only) – Motor



Motor histogram (HCP and & CIBSE)



@risk Monte Carlo histogram and statistics (CIBSE only) – Shut-off damper



Shut-off damper histogram (HCP & CIBSE)

Appendix 18. Email from Allaway Acoustics

From: Jo Corfield <Jo.Corfield@allawayacoustics.co.uk>
Sent: 16 December 2015 08:52
To: Nabil, Amir
Subject: RE: Attenuator costing

Morning Nabil,

On the information you have provided you would be looking to pay £228 per attenuator, therefore a total sum of £25,764 for 113 attenuators.

All the best in putting your model together.

Best Regards

Jo Corfield
Estimating Assistant

ALLAWAY ACOUSTICS LTD
Old Police Station, 1 Queens Road, Hertford, Herts SG14 1EN

Tel: 01992 550825
Fax: 08000 988744
Email: Jo.Corfield@allawayacoustics.co.uk
Web: http://www.allawayacoustics.co.uk

Allaway Acoustics
www.allawayacoustics.co.uk

Since 1969, Allaway Acoustics Ltd has been designing, manufacturing, and installing noise control systems across the UK. We remain an independent, specialised ...

From: Nabil, Amir [mailto:amir.nabil.12@ucl.ac.uk]
Sent: 15 December 2015 16:15
To: Jo Corfield
Subject: Fw: Attenuator costing

Hi Jo,

Thank you so much for your help! I'm at my last hurdle here as these things last so long I have no data for them.

I am looking to get a mean cost for the AHUs that I am modelling for my PhD. I have 113 in my model. The average statistically across them is:

Fan Speed: 2329rpm
Air flow: 3.21m3/s
Volume: 18.4m2
Motor rating: 7.1kw
Front surface: 2.16

Appendix 19. Crosstab Cost Table of in year Lifecycle Replacements

Option 1 -Recommended lifecycle profile crosstab for the number of parts to be replaced per year

Total	Part	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	25-26	26-27	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	36-37	37-38	38-39	39-40	40-41	41-42	42-43	43-44	44-45	45-46	46-47	47-48	48-49	49-50	50-51	51-52	52-53
81	Cooling Coils	0	0	0	0	0	0	0	1	1	3	0	7	2	6	0	0	0	0	0	0	0	4	6	7	4	0	10	6	0	8	7	0	2	0	1	1	5
42	Frost Coils	0	0	0	0	0	0	0	2	1	0	0	6	1	1	0	0	0	0	0	0	0	2	1	1	1	1	6	3	6	2	4	2	0	0	0	0	2
107	Heating Coils	0	0	0	0	0	0	0	2	11	6	0	6	1	3	0	0	0	0	0	0	0	3	11	8	14	1	4	5	3	3	9	6	2	0	1	3	5
166	Run Around	0	0	0	0	0	3	3	2	6	9	2	12	4	2	0	0	0	1	2	5	2	3	12	15	8	4	10	11	4	8	5	7	4	4	3	6	9
144	Control Panels	0	0	0	0	0	3	3	5	6	5	4	10	3	1	0	0	0	0	3	1	4	3	7	13	5	7	9	8	6	9	3	4	4	3	7	3	5
109	Supply Fans	0	0	0	0	0	0	1	3	5	9	0	6	1	7	0	0	0	0	0	0	1	5	12	11	1	2	6	3	0	11	6	3	0	0	4	8	4
96	Extract Fans	0	0	0	0	0	3	2	1	0	0	3	9	5	0	0	0	0	3	1	4	2	2	3	5	3	5	9	15	5	1	1	3	3	2	3	1	2
0	Flatbank Filters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
440	Other Filters	10	11	13	14	10	14	13	14	8	7	13	14	10	14	13	14	10	11	13	10	10	14	13	14	10	11	13	14	10	14	9	14	10	11	13	14	10
0	Polyseal Filters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
69	Humidifiers	0	0	4	2	5	0	0	2	2	0	0	0	0	0	2	5	7	1	0	7	2	3	0	0	0	0	0	5	7	3	0	4	3	1	4	0	0
178	Invertors	0	0	0	0	0	0	0	0	0	4	5	2	6	13	4	2	12	5	7	6	0	2	4	0	0	6	0	5	3	6	8	26	9	15	10	7	11
272	Motors	0	0	0	0	0	4	5	5	4	17	4	26	7	5	2	0	0	0	2	3	5	7	12	22	32	6	10	28	18	13	14	2	4	2	4	4	5
170	Shut off Dampers	0	0	0	0	0	2	1	3	5	8	2	15	5	3	0	0	0	0	1	5	1	7	9	19	3	7	16	11	8	9	0	4	2	5	0	6	13
110	Silencers	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	6	9	4	6	12	9	0	0	4	3	0	2	1	4	1	8	5	9	14	7

Option 2 -Conservative lifecycle profile crosstab for the number of parts to be replaced per year

Total	Part	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	25-26	26-27	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	36-37	37-38	38-39	39-40	40-41	41-42	42-43	43-44	44-45	45-46	46-47	47-48	48-49	49-50	50-51	51-52	52-53
113	Cooling Coils	0	0	0	0	0	0	0	1	1	3	0	7	2	6	0	1	1	4	5	1	2	6	5	8	2	7	1	9	3	9	3	1	0	6	4	11	4
51	Frost Coils	0	0	0	0	0	0	0	2	1	0	0	6	1	1	0	0	0	0	2	0	1	1	2	5	2	2	0	7	1	6	2	0	0	2	1	5	1
154	Heating Coils	0	0	0	0	0	0	0	2	11	6	0	6	1	3	0	2	2	8	8	2	1	13	4	9	2	8	0	11	5	12	4	2	2	9	6	12	3
230	Run Around	0	0	0	0	0	3	3	2	6	9	2	12	7	2	4	2	6	9	7	4	5	12	6	16	8	13	5	12	6	12	5	4	8	6	19	7	8
165	Control Panels	0	0	0	0	0	3	3	5	6	5	4	10	3	1	0	0	1	2	3	4	3	10	12	14	4	7	12	6	3	3	5	7	3	6	9	5	6
142	Supply Fans	0	0	0	0	0	0	1	3	5	9	0	6	1	7	0	1	4	8	3	5	1	7	3	5	4	6	6	8	7	8	4	4	2	4	7	11	2
126	Extract Fans	0	0	0	0	0	3	2	1	0	0	3	9	8	0	3	2	1	1	2	2	4	8	3	11	8	12	3	6	0	2	6	0	7	4	5	7	3
0	Flatbank Filters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
403	Other Filters	10	14	10	10	10	14	10	8	10	11	13	7	13	11	13	7	13	11	11	10	10	14	10	10	10	14	10	10	10	12	13	7	13	11	13	7	13
0	Polyseal Filters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80	Humidifiers	0	0	4	2	5	0	0	2	2	0	0	0	0	6	5	4	0	0	5	2	3	2	1	4	4	2	0	3	1	4	1	2	3	5	4	2	2
202	Invertors	0	0	0	0	0	0	0	0	0	4	5	2	6	13	4	2	12	5	7	8	4	2	8	4	2	11	14	5	15	6	8	12	13	12	3	12	3
335	Motors	0	0	0	0	0	4	5	5	4	17	4	26	7	7	5	1	3	9	5	18	9	10	9	20	9	20	13	23	13	13	10	19	6	17	5	10	9
192	Shut off Dampers	0	0	0	0	0	2	1	3	5	8	2	15	5	3	1	2	3	1	4	12	6	4	13	5	11	6	14	7	11	9	11	4	2	6	3	1	12
110	Silencers	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	6	9	4	6	12	9	0	0	4	0	3	2	3	2	1	8	5	14	9	7

Option 3 -Balanced lifecycle profile crosstab for the number of parts to be replaced per year

Total	Part	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	25-26	26-27	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	36-37	37-38	38-39	39-40	40-41	41-42	42-43	43-44	44-45	45-46	46-47	47-48	48-49	49-50	50-51	51-52	52-53
86	Cooling Coils	0	0	0	0	0	0	0	1	1	3	0	7	2	6	0	0	0	0	2	3	3	4	2	6	3	7	5	3	4	7	8	3	1	2	0	2	1
42	Frost Coils	0	0	0	0	0	0	0	2	1	0	0	6	1	1	0	0	0	0	0	0	0	2	1	1	2	4	4	1	3	5	4	2	0	0	0	2	0
120	Heating Coils	0	0	0	0	0	0	0	2	11	6	0	6	1	3	0	0	0	0	2	2	10	8	3	11	4	4	4	1	5	11	6	8	2	4	2	2	2
179	Run Around	0	0	0	0	0	3	3	2	6	9	2	12	4	2	1	2	1	4	2	5	10	8	8	9	4	9	13	4	8	11	9	11	3	3	3	5	3
167	Control Panels	0	0	0	0	0	3	3	5	6	5	4	10	3	1	0	0	0	1	5	4	3	9	21	7	4	13	10	4	4	1	7	1	4	3	7	12	7
114	Supply Fans	0	0	0	0	0	0	1	3	5	9	0	6	1	7	0	0	0	0	2	3	10	6	2	6	3	4	4	1	7	7	9	10	1	3	1	2	1
103	Extract Fans	0	0	0	0	0	3	2	1	0	0	3	9	5	0	1	2	1	4	1	1	2	1	8	5	2	7	17	5	6	3	0	2	1	0	5	4	2
0	Flatbank Filters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
470	Other Filters	13	8	14	14	13	11	14	13	11	10	14	11	13	14	14	14	13	11	13	13	13	14	11	14	13	11	14	14	13	13	13	14	13	8	14	14	13
0	Polyseal Filters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	Humidifiers	0	0	4	2	5	0	0	2	2	0	0	4	3	7	1	0	7	5	0	0	0	4	9	2	0	4	3	5	0	0	4	8	3	0	0	7	2
181	Invertors	0	0	0	0	0	0	0	0	0	4	5	2	6	13	4	2	12	5	7	6	0	2	6	4	0	1	7	1	10	4	25	10	9	15	4	14	3
307	Motors	0	0	0	0	0	4	5	5	4	17	4	26	7	5	2	0	5	0	4	3	11	19	15	10	15	12	23	11	12	12	14	11	15	10	15	4	7
178	Shut off Dampers	0	0	0	0	0	2	1	3	5	8	2	15	5	3	0	0	1	2	3	2	6	12	11	8	4	16	12	3	11	7	6	5	3	8	6	3	5
70	Silencers	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	6	9	4	6	12	9	0	0	3	0	0	2	0	1	3	0	1	3	2	3

Option 4 -Optimistic lifecycle profile crosstab for the number of parts to be replaced per year

Total	Part	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	25-26	26-27	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	36-37	37-38	38-39	39-40	40-41	41-42	42-43	43-44	44-45	45-46	46-47	47-48	48-49	49-50	50-51	51-52	52-53
81	Cooling Coils	0	0	0	0	0	0	0	1	1	3	0	7	2	6	0	0	0	0	2	0	3	1	3	2	1	1	5	10	3	4	3	4	0	9	3	7	0
40	Frost Coils	0	0	0	0	0	0	0	2	1	0	0	6	1	1	0	0	0	0	0	0	0	0	0	2	0	1	0	5	3	2	1	1	0	7	1	6	0
112	Heating Coils	0	0	0	0	0	0	0	2	11	6	0	6	1	3	0	0	0	0	2	2	6	2	6	2	2	1	6	11	6	3	3	6	1	10	4	10	0
168	Run Around	0	0	0	0	0	3	3	2	6	9	2	12	4	2	1	2	0	1	4	4	10	2	4	6	3	5	9	10	5	8	9	6	8	11	4	13	0
131	Control Panels	0	0	0	0	0	3	3	5	6	5	4	10	3	1	0	0	0	0	1	2	1	4	2	7	8	7	4	4	6	9	8	6	6	6	3	3	4
109	Supply Fans	0	0	0	0	0	0	1	3	5	9	0	6	1	7	0	0	0	0	1	3	8	2	4	2	1	1	4	6	6	4	2	8	1	9	6	9	0
93	Extract Fans	0	0	0	0	0	3	2	1	0	0	3	9	5	0	1	2	0	2	3	0	1	1	2	5	3	5	5	4	5	8	10	4	4	1	1	3	0
0	Flatbank Filters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
427	Other Filters	6	12	14	14	9	11	14	13	8	13	11	9	14	14	14	5	13	13	14	9	11	14	9	13	10	13	9	14	14	11	5	14	13	8	11	14	14
0	Polyseal Filters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	Humidifiers	0	0	4	2	5	0	0	2	2	0	0	0	0	0	2	5	4	2	2	0	4	1	2	2	4	1	3	1	3	2	0	0	2	1	5	2	2
143	Invertors	0	0	0	0	0	0	0	0	0	4	5	2	6	13	4	2	12	5	7	6	0	2	4	2	4	0	1	5	7	2	18	6	2	9	9	1	5
257	Motors	0	0	0	0	0	4	5	5	4	17	4	26	7	5	0	0	4	3	0	1	5	9	18	5	8	3	6	6	7	4	16	20	14	8	16	12	15
163	Shut off Dampers	0	0	0	0	0	2	1	3	5	8	2	15	5	3	0	0	0	1	1	2	5	3	8	6	5	2	3	6	8	12	6	10	6	8	9	8	10
68	Silencers	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	6	9	4	6	12	9	0	0	3	0	0	2	0	1	0	3	0	1	2	4

Appendix 20. Crosstab Cost Table of in year Lifecycle Costs

Option 1 -Recommended lifecycle costing crosstab for air-handling units

Total	Part	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	25-26	26-27	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	36-37	37-38	38-39	39-40	40-41	41-42	42-43	43-44	44-45	45-46	46-47	47-48	48-49	49-50	50-51	51-52	52-53
£ 397,496	**Cooling Coils**	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 4,730	£ 4,735	£ 14,217	£ -	£ 33,241	£ 9,508	£ 28,559	£ -	£ 4,772	£ 4,780	£ 19,149	£ 23,978	£ 4,805	£ 9,629	£ 28,951	£ 24,185	£ 38,800	£ 9,729	£ 34,165	£ 4,899	£ 44,274	£ 14,828	£ 44,726	£ 15,002	£ 5,037	£ -	£ 30,791	£ 20,781	£ 58,021	£ 21,504
£ 125,479	**Frost Coils**	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 5,767	£ 2,886	£ -	£ -	£ 17,367	£ 2,898	£ 2,901	£ -	£ -	£ -	£ -	£ 5,846	£ -	£ 2,935	£ 2,941	£ 5,897	£ 14,781	£ 5,930	£ 5,950	£ -	£ 20,990	£ 3,013	£ 18,175	£ 6,096	£ -	£ -	£ 6,256	£ 3,167	£ 16,075	£ 3,277
£ 753,969	**Heating Coils**	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 13,608	£ 74,910	£ 40,898	£ -	£ 40,982	£ 6,838	£ 20,539	£ -	£ 13,729	£ 13,750	£ 55,086	£ 55,182	£ 13,821	£ 6,925	£ 90,224	£ 27,829	£ 62,786	£ 13,994	£ 56,162	£ -	£ 77,835	£ 35,547	£ 85,776	£ 28,771	£ 14,490	£ 14,614	£ 66,434	£ 44,837	£ 91,042	£ 23,198
£ 365,245	**Run Around**	£ -	£ -	£ -	£ -	£ -	£ 6,350	£ 6,355	£ 4,240	£ 12,731	£ 19,115	£ 4,252	£ 25,539	£ 14,914	£ 4,266	£ 8,544	£ 4,278	£ 12,852	£ 19,309	£ 15,044	£ 8,613	£ 10,788	£ 25,950	£ 13,007	£ 34,778	£ 17,441	£ 28,436	£ 10,978	£ 26,457	£ 13,291	£ 26,726	£ 11,206	£ 9,030	£ 18,214	£ 13,800	£ 44,240	£ 16,547	£ 19,275
£ 496,059	**Control Panels**	£ -	£ -	£ -	£ -	£ -	£ 9,960	£ 9,968	£ 16,626	£ 19,969	£ 16,657	£ 13,338	£ 33,381	£ 10,026	£ 3,346	£ -	£ -	£ 3,360	£ 6,730	£ 10,113	£ 13,510	£ 10,153	£ 33,919	£ 40,803	£ 47,732	£ 13,678	£ 24,017	£ 41,325	£ 20,749	£ 10,424	£ 10,480	£ 17,576	£ 24,785	£ 10,713	£ 21,645	£ 32,869	£ 18,539	£ 22,675
£ 195,214	**Supply Fans**	£ -	£ -	£ -	£ -	£ -	£ -	£ 1,724	£ 5,176	£ 8,635	£ 15,557	£ -	£ 10,393	£ 1,734	£ 12,153	£ -	£ 1,741	£ 6,974	£ 13,970	£ 5,248	£ 8,763	£ 1,756	£ 12,320	£ 5,293	£ 8,846	£ 7,098	£ 10,682	£ 10,722	£ 14,355	£ 12,621	£ 14,502	£ 7,296	£ 7,349	£ 3,706	£ 7,488	£ 13,266	£ 21,164	£ 3,922
£ 171,182	**Extract Fans**	£ -	£ -	£ -	£ -	£ -	£ 5,168	£ 3,448	£ 1,725	£ -	£ -	£ 5,191	£ 15,589	£ 13,873	£ -	£ 5,215	£ 3,482	£ 1,743	£ 1,746	£ 3,498	£ 3,505	£ 7,024	£ 14,080	£ 5,293	£ 19,460	£ 14,195	£ 21,364	£ 5,361	£ 10,767	£ -	£ 3,625	£ 10,944	£ -	£ 12,971	£ 7,488	£ 9,475	£ 13,468	£ 5,883
£ -	**Flatbank Filters**	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
£ 400,021	**Other Filters**	£ 8,805	£ 12,334	£ 8,816	£ 8,822	£ 8,828	£ 12,368	£ 8,841	£ 7,079	£ 8,857	£ 9,751	£ 11,536	£ 6,218	£ 11,561	£ 9,794	£ 11,590	£ 6,249	£ 11,623	£ 9,851	£ 9,868	£ 8,988	£ 9,006	£ 12,637	£ 9,048	£ 9,073	£ 9,100	£ 12,782	£ 9,164	£ 9,202	£ 9,246	£ 11,155	£ 12,161	£ 6,596	£ 12,354	£ 10,560	£ 12,634	£ 6,907	£ 13,074
£ -	**Polyseal Filters**	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
£ 385,795	**Humidifiers**	£ -	£ -	£ 21,671	£ 10,843	£ 27,126	£ -	£ -	£ 10,876	£ 10,886	£ -	£ -	£ -	£ -	£ 32,831	£ 27,394	£ 21,946	£ -	£ -	£ 27,565	£ 11,047	£ 16,604	£ 11,094	£ 5,561	£ 22,303	£ 22,369	£ 11,222	£ -	£ 16,966	£ 5,682	£ 22,852	£ 5,749	£ 11,581	£ 17,520	£ 29,498	£ 23,890	£ 12,127	£ 12,361
£ 573,912	**Invertors**	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 12,306	£ 15,397	£ 6,165	£ 18,517	£ 40,169	£ 12,376	£ 6,196	£ 37,233	£ 15,539	£ 21,792	£ 24,952	£ 12,501	£ 6,265	£ 25,120	£ 12,594	£ 6,316	£ 34,853	£ 44,523	£ 15,968	£ 48,130	£ 19,356	£ 25,970	£ 39,238	£ 42,871	£ 39,978	£ 10,118	£ 41,090	£ 10,470
£ 447,295	**Motors**	£ -	£ -	£ -	£ -	£ -	£ 6,372	£ 7,972	£ 7,978	£ 6,388	£ 27,176	£ 6,401	£ 41,648	£ 11,226	£ 11,239	£ 8,038	£ 1,610	£ 4,837	£ 14,534	£ 8,088	£ 29,172	£ 14,616	£ 16,276	£ 14,685	£ 32,721	£ 14,768	£ 32,928	£ 21,483	£ 38,167	£ 21,675	£ 21,793	£ 16,868	£ 32,282	£ 10,282	£ 29,429	£ 8,763	£ 17,793	£ 16,321
£ 359,058	**Shut off Dampers**	£ -	£ -	£ -	£ -	£ -	£ 4,062	£ 2,033	£ 6,104	£ 10,182	£ 16,306	£ 4,080	£ 30,636	£ 10,223	£ 6,141	£ 2,050	£ 4,105	£ 6,167	£ 2,059	£ 8,250	£ 24,797	£ 12,424	£ 8,301	£ 27,045	£ 10,430	£ 23,014	£ 12,595	£ 29,498	£ 14,811	£ 23,384	£ 19,236	£ 23,658	£ 8,665	£ 4,370	£ 13,243	£ 6,703	£ 2,269	£ 27,747
£ 32,737	**Silencers**	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 852	£ 853	£ -	£ -	£ 1,714	£ 2,575	£ 1,147	£ 1,724	£ 3,455	£ 2,598	£ -	£ -	£ 1,165	£ -	£ 881	£ 590	£ 890	£ 597	£ 301	£ 2,425	£ 1,531	£ 4,340	£ 2,833	£ 2,245

Option 2 -Conservative lifecycle costing crosstab for air-handling units

Total	Part	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	25-26	26-27	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	36-37	37-38	38-39	39-40	40-41	41-42	42-43	43-44	44-45	45-46	46-47	47-48	48-49	49-50	50-51	51-52	52-53
£ 557,795	Cooling Coils	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 4,730	£ 4,735	£ 14,217	£ -	£ 33,241	£ 9,508	£ 28,559	£ -	£ 4,772	£ 4,780	£ 19,149	£ 23,978	£ 4,805	£ 9,629	£ 28,951	£ 24,185	£ 38,800	£ 9,729	£ 34,165	£ 4,899	£ 44,274	£ 14,828	£ 44,726	£ 15,002	£ 5,037	£ -	£ 30,791	£ 20,781	£ 58,021	£ 21,504
£ 153,147	Frost Coils	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 5,767	£ 2,886	£ -	£ -	£ 17,367	£ 2,898	£ 2,901	£ -	£ -	£ -	£ -	£ 5,846	£ -	£ 2,935	£ 2,941	£ 5,897	£ 14,781	£ 5,930	£ 5,950	£ -	£ 20,990	£ 3,013	£ 18,175	£ 6,096	£ -	£ -	£ 6,256	£ 3,167	£ 16,075	£ 3,277
£ 1,089,809	Heating Coils	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 13,608	£ 74,910	£ 40,898	£ -	£ 40,982	£ 6,838	£ 20,539	£ -	£ 13,729	£ 13,750	£ 55,086	£ 55,182	£ 13,821	£ 6,925	£ 90,224	£ 27,829	£ 62,786	£ 13,994	£ 56,162	£ -	£ 77,835	£ 35,547	£ 85,776	£ 28,771	£ 14,490	£ 14,614	£ 66,434	£ 44,837	£ 91,042	£ 23,198
£ 506,566	Run Around	£ -	£ -	£ -	£ -	£ -	£ 6,350	£ 6,355	£ 4,240	£ 12,731	£ 19,115	£ 4,252	£ 25,539	£ 14,914	£ 4,266	£ 8,544	£ 4,278	£ 12,852	£ 19,309	£ 15,044	£ 8,613	£ 10,788	£ 25,950	£ 13,007	£ 34,778	£ 17,441	£ 28,436	£ 10,978	£ 26,457	£ 13,291	£ 26,726	£ 11,206	£ 9,030	£ 18,214	£ 13,800	£ 44,240	£ 16,547	£ 19,275
£ 569,065	Control Panels	£ -	£ -	£ -	£ -	£ -	£ 9,960	£ 9,968	£ 16,626	£ 19,969	£ 16,657	£ 13,338	£ 33,381	£ 10,026	£ 3,346	£ -	£ -	£ 3,360	£ 6,730	£ 10,113	£ 13,510	£ 10,153	£ 33,919	£ 40,803	£ 47,732	£ 13,678	£ 24,017	£ 41,325	£ 20,749	£ 10,424	£ 10,480	£ 17,576	£ 24,785	£ 10,713	£ 21,645	£ 32,869	£ 18,539	£ 22,675
£ 254,452	Supply Fans	£ -	£ -	£ -	£ -	£ -	£ -	£ 1,724	£ 5,176	£ 8,635	£ 15,557	£ -	£ 10,393	£ 1,734	£ 12,153	£ -	£ 1,741	£ 6,974	£ 13,970	£ 5,248	£ 8,763	£ 1,756	£ 12,320	£ 5,293	£ 8,846	£ 7,098	£ 10,682	£ 10,722	£ 14,355	£ 12,621	£ 14,502	£ 7,296	£ 7,349	£ 3,706	£ 7,488	£ 13,266	£ 21,164	£ 3,922
£ 225,584	Extract Fans	£ -	£ -	£ -	£ -	£ -	£ 5,168	£ 3,448	£ 1,725	£ -	£ -	£ 5,191	£ 15,589	£ 13,873	£ -	£ 5,215	£ 3,482	£ 1,743	£ 1,746	£ 3,498	£ 3,505	£ 7,024	£ 14,080	£ 5,293	£ 19,460	£ 14,195	£ 21,364	£ 5,361	£ 10,767	£ -	£ 3,625	£ 10,944	£ -	£ 12,971	£ 7,488	£ 9,475	£ 13,468	£ 5,883
£ -	Flatbank Filters	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
£ 366,477	Other Filters	£ 8,805	£ 12,334	£ 8,816	£ 8,822	£ 8,828	£ 12,368	£ 8,841	£ 7,079	£ 8,857	£ 9,751	£ 11,536	£ 6,218	£ 11,561	£ 9,794	£ 11,590	£ 6,249	£ 11,623	£ 9,851	£ 9,868	£ 8,988	£ 9,006	£ 12,637	£ 9,048	£ 9,073	£ 9,100	£ 12,782	£ 9,164	£ 9,202	£ 9,246	£ 11,155	£ 12,161	£ 6,596	£ 12,354	£ 10,560	£ 12,634	£ 6,907	£ 13,074
£ -	Polyseal Filters	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
£ 449,564	Humidifiers	£ -	£ -	£ 21,671	£ 10,843	£ 27,126	£ -	£ -	£ 10,876	£ 10,886	£ -	£ -	£ -	£ -	£ 32,831	£ 27,394	£ 21,946	£ -	£ -	£ 27,565	£ 11,047	£ 16,604	£ 11,094	£ 5,561	£ 22,303	£ 22,369	£ 11,222	£ -	£ 16,966	£ 5,682	£ 22,852	£ 5,749	£ 11,581	£ 17,520	£ 29,498	£ 23,890	£ 12,127	£ 12,361
£ 646,002	Invertors	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 12,306	£ 15,397	£ 6,165	£ 18,517	£ 40,169	£ 12,376	£ 6,196	£ 37,233	£ 15,539	£ 21,792	£ 24,952	£ 12,501	£ 6,265	£ 25,120	£ 12,594	£ 6,316	£ 34,853	£ 44,523	£ 15,968	£ 48,130	£ 19,356	£ 25,970	£ 39,238	£ 42,871	£ 39,978	£ 10,118	£ 41,090	£ 10,470
£ 553,529	Motors	£ -	£ -	£ -	£ -	£ -	£ 6,372	£ 7,972	£ 7,978	£ 6,388	£ 27,176	£ 6,401	£ 41,648	£ 11,226	£ 11,239	£ 8,038	£ 1,610	£ 4,837	£ 14,534	£ 8,088	£ 29,172	£ 14,616	£ 16,276	£ 14,685	£ 32,721	£ 14,768	£ 32,928	£ 21,483	£ 38,167	£ 21,675	£ 21,793	£ 16,868	£ 32,282	£ 10,282	£ 29,429	£ 8,763	£ 17,793	£ 16,321
£ 404,589	Shut off Dampers	£ -	£ -	£ -	£ -	£ -	£ 4,062	£ 2,033	£ 6,104	£ 10,182	£ 16,306	£ 4,080	£ 30,636	£ 10,223	£ 6,141	£ 2,050	£ 4,105	£ 6,167	£ 2,059	£ 8,250	£ 24,797	£ 12,424	£ 8,301	£ 27,045	£ 10,430	£ 23,014	£ 12,595	£ 29,498	£ 14,811	£ 23,384	£ 19,236	£ 23,658	£ 8,665	£ 4,370	£ 13,243	£ 6,703	£ 2,269	£ 27,747
£ 32,714	Silencers	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 852	£ 853	£ -	£ -	£ 1,714	£ 2,575	£ 1,147	£ 1,724	£ 3,455	£ 2,598	£ -	£ -	£ 1,165	£ -	£ 881	£ 590	£ 890	£ 597	£ 301	£ 2,425	£ 1,531	£ 4,340	£ 2,833	£ 2,245

Option 3 -Balanced lifecycle costing crosstab for air-handling units

Total	Part	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	25-26	26-27	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	36-37	37-38	38-39	39-40	40-41	41-42	42-43	43-44	44-45	45-46	46-47	47-48	48-49	49-50	50-51	51-52	52-53
£ 420,465	Cooling Coils	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 4,730	£ 4,735	£ 14,217	£ -	£ 33,241	£ 9,508	£ 28,559	£ -	£ -	£ -	£ -	£ 9,591	£ 14,414	£ 14,443	£ 19,301	£ 9,674	£ 29,100	£ 14,594	£ 34,165	£ 24,494	£ 14,758	£ 19,771	£ 34,787	£ 40,004	£ 15,111	£ 5,080	£ 10,264	£ -	£ 10,549	£ 5,376
£ 125,325	Frost Coils	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 5,767	£ 2,886	£ -	£ -	£ 17,367	£ 2,898	£ 2,901	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 5,882	£ 2,948	£ 2,956	£ 5,930	£ 11,900	£ 11,944	£ 2,999	£ 9,038	£ 15,146	£ 12,192	£ 6,140	£ -	£ -	£ -	£ 6,430	£ -
£ 844,121	Heating Coils	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 13,608	£ 74,910	£ 40,898	£ -	£ 40,982	£ 6,838	£ 20,539	£ -	£ -	£ -	£ -	£ 13,795	£ 13,821	£ 69,249	£ 55,523	£ 20,872	£ 76,738	£ 27,988	£ 28,081	£ 28,186	£ 7,076	£ 35,547	£ 78,628	£ 43,156	£ 57,959	£ 14,614	£ 29,526	£ 14,946	£ 15,174	£ 15,466
£ 392,107	Run Around	£ -	£ -	£ -	£ -	£ -	£ 6,350	£ 6,355	£ 4,240	£ 12,731	£ 19,115	£ 4,252	£ 25,539	£ 8,522	£ 4,266	£ 2,136	£ 4,278	£ 2,142	£ 8,582	£ 4,298	£ 10,766	£ 21,577	£ 17,300	£ 17,342	£ 19,563	£ 8,721	£ 19,687	£ 28,542	£ 8,819	£ 17,721	£ 24,499	£ 20,170	£ 24,831	£ 6,830	£ 6,900	£ 6,985	£ 11,820	£ 7,228
£ 576,661	Control Panels	£ -	£ -	£ -	£ -	£ -	£ 9,960	£ 9,968	£ 16,626	£ 19,969	£ 16,657	£ 13,338	£ 33,381	£ 10,026	£ 3,346	£ -	£ -	£ -	£ 3,365	£ 16,855	£ 13,510	£ 10,153	£ 30,527	£ 71,404	£ 23,866	£ 13,678	£ 44,603	£ 34,437	£ 13,833	£ 13,898	£ 3,493	£ 24,606	£ 3,541	£ 14,284	£ 10,823	£ 25,565	£ 44,494	£ 26,454
£ 203,052	Supply Fans	£ -	£ -	£ -	£ -	£ -	£ -	£ 1,724	£ 5,176	£ 8,635	£ 15,557	£ -	£ 10,393	£ 1,734	£ 12,153	£ -	£ -	£ -	£ -	£ 3,498	£ 5,258	£ 17,561	£ 10,560	£ 3,529	£ 10,615	£ 5,323	£ 7,121	£ 7,148	£ 1,794	£ 12,621	£ 12,689	£ 16,416	£ 18,373	£ 1,853	£ 5,616	£ 1,895	£ 3,848	£ 1,961
£ 183,713	Extract Fans	£ -	£ -	£ -	£ -	£ -	£ 5,168	£ 3,448	£ 1,725	£ -	£ -	£ 5,191	£ 15,589	£ 8,671	£ -	£ 1,738	£ 3,482	£ 1,743	£ 6,985	£ 1,749	£ 1,753	£ 3,512	£ 1,760	£ 14,115	£ 8,846	£ 3,549	£ 12,462	£ 30,378	£ 8,972	£ 10,818	£ 5,438	£ -	£ 3,675	£ 1,853	£ -	£ 9,475	£ 7,696	£ 3,922
£ -	Flatbank Filters	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
£ 427,460	Other Filters	£ 11,446	£ 7,048	£ 12,342	£ 12,350	£ 11,476	£ 9,718	£ 12,378	£ 11,504	£ 9,742	£ 8,865	£ 12,423	£ 9,771	£ 11,561	£ 12,465	£ 12,481	£ 12,499	£ 11,623	£ 9,851	£ 11,662	£ 11,684	£ 11,708	£ 12,637	£ 9,953	£ 12,702	£ 11,830	£ 10,043	£ 12,830	£ 12,883	£ 12,020	£ 12,085	£ 12,161	£ 13,191	£ 12,354	£ 7,680	£ 13,606	£ 13,814	£ 13,074
£ -	Polyseal Filters	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
£ 522,042	Humidifiers	£ -	£ -	£ 21,671	£ 10,843	£ 27,126	£ -	£ -	£ 10,876	£ 10,886	£ -	£ -	£ 21,837	£ 16,396	£ 38,303	£ 5,479	£ -	£ 38,462	£ 27,517	£ -	£ -	£ -	£ 22,188	£ 50,046	£ 11,151	£ -	£ 22,444	£ 16,895	£ 28,277	£ -	£ -	£ 22,995	£ 46,324	£ 17,520	£ -	£ -	£ 42,446	£ 12,361
£ 581,122	Invertors	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 12,306	£ 15,397	£ 6,165	£ 18,517	£ 40,169	£ 12,376	£ 6,196	£ 37,233	£ 15,539	£ 21,792	£ 18,714	£ -	£ 6,265	£ 18,840	£ 12,594	£ -	£ 3,168	£ 22,262	£ 3,194	£ 32,087	£ 12,904	£ 81,156	£ 32,698	£ 29,680	£ 49,972	£ 13,491	£ 47,938	£ 10,470
£ 507,599	Motors	£ -	£ -	£ -	£ -	£ -	£ 6,372	£ 7,972	£ 7,978	£ 6,388	£ 27,176	£ 6,401	£ 41,648	£ 11,226	£ 8,028	£ 3,215	£ -	£ 8,061	£ -	£ 6,471	£ 4,862	£ 17,864	£ 30,925	£ 24,475	£ 16,360	£ 24,614	£ 19,757	£ 38,008	£ 18,254	£ 20,008	£ 20,116	£ 23,615	£ 18,690	£ 25,704	£ 17,311	£ 26,288	£ 7,117	£ 12,694
£ 374,815	Shut off Dampers	£ -	£ -	£ -	£ -	£ -	£ 4,062	£ 2,033	£ 6,104	£ 10,182	£ 16,306	£ 4,080	£ 30,636	£ 10,223	£ 6,141	£ -	£ -	£ 2,056	£ 4,118	£ 6,188	£ 4,133	£ 12,424	£ 24,903	£ 22,884	£ 16,688	£ 8,369	£ 33,587	£ 25,284	£ 6,347	£ 23,384	£ 14,962	£ 12,904	£ 10,832	£ 6,555	£ 17,658	£ 13,407	£ 6,806	£ 11,561
£ 20,409	Silencers	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 852	£ 853	£ -	£ -	£ 1,714	£ 2,575	£ 1,147	£ 1,724	£ 3,455	£ 2,598	£ -	£ -	£ 874	£ -	£ -	£ 590	£ -	£ 298	£ 902	£ -	£ 306	£ 930	£ 629	£ 962

Option 4 -Optimistic lifecycle costing crosstab for air-handling units

Total	Part	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	25-26	26-27	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	36-37	37-38	38-39	39-40	40-41	41-42	42-43	43-44	44-45	45-46	46-47	47-48	48-49	49-50	50-51	51-52	52-53
£ 400,044	Cooling Coils	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 4,730	£ 4,735	£ 14,217	£ -	£ 33,241	£ 9,508	£ 28,559	£ -	£ -	£ -	£ -	£ 9,591	£ -	£ 14,443	£ 4,825	£ 14,511	£ 9,700	£ 4,865	£ 4,881	£ 24,494	£ 49,194	£ 14,828	£ 19,878	£ 15,002	£ 20,148	£ -	£ 46,187	£ 15,586	£ 36,922	£ -
£ 121,268	Frost Coils	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 5,767	£ 2,886	£ -	£ -	£ 17,367	£ 2,898	£ 2,901	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 5,913	£ -	£ 2,975	£ -	£ 14,993	£ 9,038	£ 6,058	£ 3,048	£ 3,070	£ -	£ 21,897	£ 3,167	£ 19,290	£ -
£ 793,678	Heating Coils	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 13,608	£ 74,910	£ 40,898	£ -	£ 40,982	£ 6,838	£ 20,539	£ -	£ -	£ -	£ -	£ 13,795	£ 13,821	£ 41,549	£ 13,881	£ 41,744	£ 13,952	£ 13,994	£ 7,020	£ 42,278	£ 77,835	£ 42,657	£ 21,444	£ 21,578	£ 43,470	£ 7,307	£ 73,815	£ 29,891	£ 75,869	£ -
£ 370,204	Run Around	£ -	£ -	£ -	£ -	£ -	£ 6,350	£ 6,355	£ 4,240	£ 12,731	£ 19,115	£ 4,252	£ 25,539	£ 8,522	£ 4,266	£ 2,136	£ 4,278	£ -	£ 2,145	£ 8,597	£ 8,613	£ 21,577	£ 4,325	£ 8,671	£ 13,042	£ 6,540	£ 10,937	£ 19,760	£ 22,047	£ 11,076	£ 17,818	£ 20,170	£ 13,544	£ 18,214	£ 25,299	£ 9,314	£ 30,731	£ -
£ 451,918	Control Panels	£ -	£ -	£ -	£ -	£ -	£ 9,960	£ 9,968	£ 16,626	£ 19,969	£ 16,657	£ 13,338	£ 33,381	£ 10,026	£ 3,346	£ -	£ -	£ -	£ -	£ 3,371	£ 6,755	£ 3,384	£ 13,568	£ 6,800	£ 23,866	£ 27,357	£ 24,017	£ 13,775	£ 13,833	£ 20,847	£ 31,440	£ 28,122	£ 21,244	£ 21,426	£ 21,645	£ 10,956	£ 11,124	£ 15,117
£ 195,815	Supply Fans	£ -	£ -	£ -	£ -	£ -	£ -	£ 1,724	£ 5,176	£ 8,635	£ 15,557	£ -	£ 10,393	£ 1,734	£ 12,153	£ -	£ -	£ -	£ -	£ 1,749	£ 5,258	£ 14,049	£ 3,520	£ 7,057	£ 3,538	£ 1,774	£ 1,780	£ 7,148	£ 10,767	£ 10,818	£ 7,251	£ 3,648	£ 14,698	£ 1,853	£ 16,847	£ 11,370	£ 17,316	£ -
£ 166,037	Extract Fans	£ -	£ -	£ -	£ -	£ -	£ 5,168	£ 3,448	£ 1,725	£ -	£ -	£ 5,191	£ 15,589	£ 8,671	£ -	£ 1,738	£ 3,482	£ -	£ 3,492	£ 5,248	£ -	£ 1,756	£ 1,760	£ 3,529	£ 8,846	£ 5,323	£ 8,902	£ 8,935	£ 7,178	£ 9,015	£ 14,502	£ 18,240	£ 7,349	£ 7,412	£ 1,872	£ 1,895	£ 5,772	£ -
£ -	Flatbank Filters	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
£ 388,468	Other Filters	£ 5,283	£ 10,572	£ 12,342	£ 12,350	£ 7,945	£ 9,718	£ 12,378	£ 11,504	£ 7,085	£ 11,524	£ 9,761	£ 7,995	£ 12,450	£ 12,465	£ 12,481	£ 4,464	£ 11,623	£ 11,642	£ 12,559	£ 8,089	£ 9,907	£ 12,637	£ 8,143	£ 11,795	£ 9,100	£ 11,869	£ 8,248	£ 12,883	£ 12,945	£ 10,226	£ 4,677	£ 13,191	£ 12,354	£ 7,680	£ 10,691	£ 13,814	£ 14,079
£ -	Polyseal Filters	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -
£ 364,696	Humidifiers	£ -	£ -	£ 21,671	£ 10,843	£ 27,126	£ -	£ -	£ 10,876	£ 10,886	£ -	£ -	£ -	£ -	£ -	£ 10,958	£ 27,432	£ 21,978	£ 11,007	£ 11,026	£ -	£ 22,139	£ 5,547	£ 11,121	£ 11,151	£ 22,369	£ 5,611	£ 16,895	£ 5,655	£ 17,047	£ 11,426	£ -	£ -	£ 11,680	£ 5,900	£ 29,863	£ 12,127	£ 12,361
£ 456,076	Invertors	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 12,306	£ 15,397	£ 6,165	£ 18,517	£ 40,169	£ 12,376	£ 6,196	£ 37,233	£ 15,539	£ 21,792	£ 18,714	£ -	£ 6,265	£ 12,560	£ 6,297	£ 12,632	£ -	£ 3,180	£ 15,968	£ 22,461	£ 6,452	£ 58,432	£ 19,619	£ 6,596	£ 29,983	£ 30,354	£ 3,424	£ 17,450
£ 428,141	Motors	£ -	£ -	£ -	£ -	£ -	£ 6,372	£ 7,972	£ 7,978	£ 6,388	£ 27,176	£ 6,401	£ 41,648	£ 11,226	£ 8,028	£ -	£ -	£ 6,449	£ 4,845	£ -	£ 1,621	£ 8,120	£ 14,649	£ 29,369	£ 8,180	£ 13,128	£ 4,939	£ 9,915	£ 9,957	£ 11,671	£ 6,705	£ 26,989	£ 33,982	£ 23,991	£ 13,849	£ 28,040	£ 21,351	£ 27,202
£ 346,806	Shut off Dampers	£ -	£ -	£ -	£ -	£ -	£ 4,062	£ 2,033	£ 6,104	£ 10,182	£ 16,306	£ 4,080	£ 30,636	£ 10,223	£ 6,141	£ -	£ -	£ -	£ 2,059	£ 2,063	£ 4,133	£ 10,353	£ 6,226	£ 16,643	£ 12,516	£ 10,461	£ 4,198	£ 6,321	£ 12,695	£ 17,007	£ 25,648	£ 12,904	£ 21,664	£ 13,109	£ 17,658	£ 20,110	£ 18,149	£ 23,122
£ 19,811	Silencers	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 852	£ 853	£ -	£ -	£ 1,714	£ 2,575	£ 1,147	£ 1,724	£ 3,455	£ 2,598	£ -	£ -	£ 874	£ -	£ -	£ 590	£ -	£ 298	£ -	£ 909	£ -	£ 310	£ 629	£ 1,283

Appendix 21. Palm Video

See attached CD.

Appendix 22. HCP Management Board Interview Schedule

<u>Section 1 – Introduction and Board Meeting Review</u>

Greet participant.
Interviewer reiterates the aim of the research to the interviewee.

1. How did you perceive the video presented on the PALM model at the HCP Board Meeting on December 8th 2015?

2. A part of the video illustrated a smoother profile in comparison to the current SAM model for the same assets (this is based on replacement of the part rather than the entire AHU). Results have shown that there could be more than £1m in surplus budgeted for lifecycle at [redacted]. How would visualising how this lower figure has been achieved via the PALM model impact your level of confidence in the lifecycle of air-handling units at [redacted]?

<u>Section 2 – Stakeholder understanding and future application</u>

3. The model shows what is being proposed to be replaced via an RGB visual, over time. The profile is underpinned by real cost data collected across HCP hospitals. So, how do you believe the model better informs decision-making at a strategic level?

4. Removing yourself from the current situation at [redacted] (as we are all aware of the difficult times the project faces at current), would similar visual modelling techniques increase confidence in your ability to be able to suggest distributions of the surplus lifecycle attributed to these assets?

5. What benefits, if any, do you believe modelling complex assets in this way will bring to HCP?

6. Do you think there is a need for such visualisation techniques to advance the field of lifecycle costing and management? If so, why?

7. Do you feel that the model helps to increase clarity to the process of lifecycle? If so, which stakeholders do you believe could benefit from such a tool?

8. In terms of winning work and displaying our skill set as a business, do you believe that this tool could be used as part of a business proposition for HCP going forwards?

Appendix 27. Interview Transcripts

HCP Management Board Interview Transcripts

The table below outlines the details of the interviewees. For each interview an assigned code is used to differentiate between the interviews.

Interview number	Job Title	Experience
I01	Regional Director South (RDS)	26 years
I02	Business Development Director (BDD)	15 years
I03	Chief Executive Officer (CEO)	32 years

Interview 01 Transcript

IN: How did you perceive the video presented on the PALM model at the HCP Board Meeting on December 8th 2015?

I01: It took me a while to understand what was trying to be delivered initially. Although having reflected on it I do wonder whether it's an age thing more than anything else. I think the visualisation aspect and doing things in 3D is something that may appeal to the younger generation but I am struggling with it I have to say. There's a generational gap with this sort of thing I think, although that's my opinion. I spoke with my son about your work and he completely understood how it would work.

IN: A part of the video illustrated a smoother profile in comparison to the current SAM model for the same assets (this is based on replacement of the part rather than the entire AHU). Results have shown that there could be more than £1m in surplus budgeted for lifecycle at [redacted]. How would visualising how this lower figure has been achieved via the PALM model impact your level of confidence in the lifecycle of air-handling units at [redacted]?

I01: Erm, that's something I can get my head around. For someone from a non-technical background like me I can walk into a plant room and see a big box that's an air-handling unit. What goes on behind that is an absolute dark art to me. All the component bits. So I think the visualisation that you suggested around here's a big box but here's a motor, here's whatever, that does have resonance with me and I can see that yes, there's component parts here that do make up the sum. Whereas in my quiet little world an air-handling unit has a 20-year life or whatever and after 20 years the whole lot gets stripped out and replaced. In reality I can picture that now as well no actually that motor's 5 years, those fans are 12 years and what-have-you and it's a bit like the broom example isn't it. I've had this broom for 20 years and it's had 10 handles and 5 heads. I can see now on that micro scale on something big and complex that visual aspect does work for me.

IN: The model shows what is being proposed to be replaced via an RGB visual over time. The profile is underpinned by real cost data collected across HCP hospitals. So, how do you believe the model better informs decision-making at a strategic level?

I01: Erm, the model itself brings currently what's done in disparate parts together to one point and what I mean by that is that if you look at lots of different elements that need to be replaced over time there must be a point where if you keep replacing the component parts you begin to ask whether you should carry on patching this up or should you just go out and buy a new one. I think the model you're starting to bring together shows a lot of that information in a cohesive way rather than what we've got at the moment which is very experienced people out there that know intuitively but if you ask them to evidence it, it would be quite difficult. I can start to see how decision-making can be made on fact rather than gut feel.

IN: Removing yourself from the current situation at [redacted] (as we are all aware of the difficult times the project faces at current), would similar visual modelling techniques increase confidence in your ability to be able to suggest distributions of the surplus lifecycle attributed to these assets?

I01: Erm, oh I be lying to say yes to that in isolation. I think the world we are moving into is much more based around evidence, and giving boards comfort that the evidence is there to take money out and the more we can add to that evidence base the better. I think notwithstanding the fact that I may be unique, I doubt it, I suspect that there would be a number of board directors that would look at the visualisation element and say 'not for me, don’t understand it’ give me the raw maths. There will be other people, dare I say it slightly younger, that will say ‘yeah, d’you know what, this is something that actually helps to build that argument. I think in isolation, no. As a block in a set of evidence yes, absolutely.

IN: What benefits, if any, do you believe modelling complex assets in this way will bring to HCP?

I01: Whoa, there’s a question, erm, I think there is something clearly there about if no-one else is doing this there’s got to be a USP to get out there. If we could find a way to sell that as a product and demonstrate that there is more evidence and assurance around some of this stuff, not just in stripping out lifecycle, but those organisations that are non-PFI and don’t actually have a lifecycle pot but more a lifecycle budget. There’s certainly something within that. I think within the current portfolio, erm, I think it’s incumbent on us to optimise these projects anyway so if the work that you’re doing helps to bring some security into what we can strip out of lifecycle with confidence then I think it’s positive for HCP on a number of levels. 1, it retains MSAs. 2, it increased our position in the market but also I think there’s something in there that’s a bit pink and fluffy but it seems to do a good job and looks really positive.

IN: Do you think there is a need for such visualisation techniques to advance the field of lifecycle costing and management? If so, why?

Hmm, right here and now, no however, I think if you have the conversation about any sort of advancement and technology or systems and processes it takes time and people sticking to their guns to make things happen. I suspect if we were having a similar conversation in a number of years’ time the answers probably yes. It comes back to me that there’s always horses for courses. It’s not going to work for everybody and I think that it would be foolish to think that it would. I suspect it’s the sort of thing that if it became industry norm then of course it will become what people expect and dare I say it a minimum in future.

IN: Do you feel that the model helps to increase clarity to the process of lifecycle? If so, which stakeholders do you believe could benefit from such a tool?

I01: I think all of the previous really. Yes, in some cases it’s going to help and some of the stakeholders that will benefit will be the ones that see it for what it is and almost bring together a few with a little scepticism like me. It goes back to earlier and digging into the detail of the kit the elemental view leads onto better things. In terms of which stakeholders will benefit I think it’s going to be a personal thing and dependent on whether they can get their head around the concept.

IN: In terms of winning work and displaying our skill set as a business, do you believe that this tool could be used as part of a business proposition for HCP going forwards?

I01: Yes, absolutely and I think the cutting edge of being able to put something out there that says ‘this is new, no one else is doing this at the moment but you mark my words they will all be doing it in 10 years’ time or 15 years’ time’ or whatever will absolutely be a sell. Both in terms of showing HCP as a company that is modern and moving forwards and not just staying in its ways as the rest of PFI tends to be but also in terms of that it will also get people’s attention even if they don’t believe in its entirety what it is that you’ve put in front of them. But I sign up to the fact that if we put ourselves forward as being innovators and people like you in the organisation that can turn that conceptual stuff into reality then the impression people have of HCP is different to one of us just plodding and being as good as the next. I think there’s lots of opportunities there in terms of presentation and perception of the organisation in the wider world.

Interview 02 Transcript

IN: How did you perceive the video presented on the PALM model at the HCP Board Meeting on December 8th 2015?
I02: I think the overall visual evidenced a lot of work and I think the quality in my view was very good. There are certain aspects which I thought were quite helpful in a sense that it represented an overall system if you will. I think you gave me the knowledge of how extensive that system really is which I think enhances the investors and decision-makers' appreciation of some of the complexities in decision-making. It's not just one unit or a series, it's actually a whole system you need to consider. Erm, I think there was a lot of flying through and seeing this collection of units which was helpful, beneficial. Personally I think we could have lessened the amount of time we spent on the system as a whole as opposed to the individual components. From memory I think the system allows for visualisation of internal components of each unit. By equally I think it would have been nice to see you fly all the way into the centre of each subcomponent of the unit and make explicit the lifecycle implications of the funding model and the wider system as a whole. I think that would be something that would be interesting to explore in future visualisations. Overall I thought that it does highlight that model may be applied to other systems as well. So here we are modelling AHUs but elsewhere is could be M&E and other systems that form part of the long-term lifecycle of the [redacted] building or any other building for that matter. I think that was a good message, I could see a full model of an entire building and which key components or parts are subject to lifecycle expenditure in year 1, year 2 year 5 and throughout the whole concession which I think is visually very powerful and it brings home the complexity and I think it does aid in appreciating in the scale of any potential investment. I think also possibly linking the units to areas of criticality of which they are located brings home the message that some units are more important than others for the [purposes of ensuring performance. That's already highlighted in the model through virtue of different colour schemes but maybe some of the context around the location of the unit may be a future possibility. I thought it was helpful, as you're aware I am already pushing for this model to be combined with some of the analytics in our funding model so that visually or presentationally you get the visual of the component alongside the analytics. I think the two juxtaposed would be quite powerful for the investor as you present to them.

IN: A part of the video illustrated a smoother profile in comparison to the current SAM model for the same assets (this is based on replacement of the part rather than the entire AHU). Results have shown that there could be more than £1m in surplus budgeted for lifecycle at [redacted]. How would visualising how this lower figure has been achieved via the PALM model impact your level of confidence in the lifecycle of air-handling units at [redacted]?
I02: I think this is probably the area of what could have been brought out more forcefully in the presentation. What I took away from the visualisation was the different colour schemes underpinned by the model calculations and criticality. What I didn't get was the sense of

time perspective, so when does this actually happen. I do think that your suggestion of looking at savings via individual subcomponents plays to my first comment namely that in the fly through you could have a focus on the subcomponents, thereby telling the story that by replacing subcomponents' there's a significant economic benefit accruing to the lifecycle budget.

IN: The model shows what is being proposed to be replaced via an RGB visual over time. The profile is underpinned by real cost data collected across HCP hospitals. So, how do you believe the model better informs decision-making at a strategic level?

I think as an investor or decision-maker I would probably expect to have the summary of the analytics presented to me first so that the assumptions and wider parameters of the capex investment is made explicit before. I think then the visualisation enhances where exactly there is impact within the wider system and it may also enhance your understanding of what the subcomponents are saying according to the investment choice. Again, having an understanding, I'm not a technical person, but having an understanding of what an air-handling unit actually looks like and what these subcomponents actually look like, the context in which they placed, some of the issues which may be given rise to their replacement I think is informative and very useful. And perhaps also just understanding the quantities involved, not from a financial perspective but from a simple quantity perspective. How many components of X, Y, Z are there, do we have those? Are they obsolete? Do we need to buy them from eBay? Etc etc etc Those sort of ramifications I think would be quite good but I think the visualisation component does add an understanding of the physical parameters you have to operate in to in order to actually deliver a replacement strategy.

IN: Removing yourself from the current situation at [redacted] (as we are all aware of the difficult times the project faces at current), would similar visual modelling techniques increase confidence in your ability to be able to suggest distributions of the surplus lifecycle attributed to these assets?

I02: I think the strength of the visualisation component is to visualise the strategy that you choose based on the risk appetite level so whether it's an optimistic, conservative, balanced or recommended approach I would expect that with each scenario you choose you get a better understanding of the extent of your decision and that's useful. Underlining the differences between a conservative balanced and optimistic scenario will impact critical units around the facility and they gain an understanding of how that impacts the wider and softer service objectives. For example, in respect of pleasing the client the NHS trust in that we will have a facility that is available that is conforming to requirement and contractual expectations. So I think that visualising different financial scenarios as set out in your graph would be useful. My suggestion would be that in the interest of time you could focus on the extremes. So what's the difference between the conservative, flythrough and optimistic, fly through, and I think that would be quite powerful. It's almost an infographic, a moving infographic. An infographic has two key components, a visual and then the info and some of the info in terms of cold numbers could be extracted as part of the visualisation and would be interesting to explore. But again that may equally be achieved by having a sequential presentation. A. This is the cumulative profile of scenario X, Y and Z. This is the financial implication and this is the visualisation of the strategy. I think that may achieve the same affect and I think there would be benefit. My suggestion as a decision-maker would be probably to base 80 or 70% of the decision-making on the numbers and 20-30% on the visualisation. It will be an important dimension.

IN: What benefits, if any, do you believe modelling complex assets in this way will bring to HCP?

I02: Well I think if you think about the types of clients that we have they are like me, financially educated. So there's an emphasis on the financial impacts of lifecycle strategy. Erm and I think the visualisation brings home some of the technical complexities in terms of what's the asset? What does it look like? Where is it located? How many are there? How does it fit into the overall fabric of the facility? What are the critical areas around the facility? Erm I guess also it may give rise to what are the potential risks to the whole facility if any or the whole system should be compromised? So I think as I mentioned before, understanding what's inside the asset would be quite useful and that visualisation will make it easier to gauge some of the risks associated with the financial appraisal of each of these scenarios. So I think there's a subtlety of understanding the system which a technical person who is in that environment every single day has which the visualisation brings to the financial decision-making and I think that's of value so in terms of the wider benefits to HCP I think there could be quite some value in using this technology in, and pardon my terminology if its incorrect, a visual BIM model which you could both use to present to investors but possibly also used to instruct your service providers in better maintenance strategies, and making us more efficient. I can easily see how an investor would be impressed with presentation which allows them to visualise, say you have whole systems modelled and you want to tell them about the critical components of the system as a whole, this brings in one fell swoop you'd be able to highlight all red categories, you'd be able ti identify them, visualising them in 3 dimensions throughout the whole complex building would be powerful and they would be able to understand, what are the complexities? What are the implications of the decision-making? Which is very difficult to gleam from a couple of lines on an expenditure graph.

IN: Do you think there is a need for such visualisation techniques to advance the field of lifecycle costing and management? If so, why?

I02: I think my previous answer tried to articulate a latent need. If you go out and ask an operator on the floor at [redacted] looking after AHUs could they articulate a current need at this time? I suspect not. Could you present them with something and then they would understand their need? Probably yes, I think there's a bit of marketing and promoting here. My intuition tells me that this should form part of an operational BIM visualisation model, I think that would be powerful. I haven't seen any such models but I think it would be quite interesting to develop that capability and integration between the two because then it makes everything very real. What do I need to do? Here's my plan for today. How do I replace that component? If you could embody this stuff and deliver it using a pair of google glasses you know, that would be a great tool for an operator to have and that would make them far more efficient in delivering their service.

IN: In terms of winning work and displaying our skill set as a business, do you believe that this tool could be used as part of a business proposition for HCP going forwards?

I02: Yeah absolutely. My concern is the amount of time it takes to generate the visuals, no doubt you worked very hard and I'd be scared considering the cost of the amount of hours you've put into it so that needs to be looked into. But there's no doubt that if you can develop a visual model of an entire building or subset of the 10 most critical assets say, erm, that would be something that would be useful in persuading the other parties in the technical prowess of this business and the level of detail and understanding of the basics of the assets under management. I think that would be a powerful message because you can't visualise something unless you have a very intricate and robust data set and that speaks volumes to people who might contemplate taking on the services of HCP.

Interview 03 Transcript

IN: How did you perceive the video presented on the PALM model at the HCP Board Meeting on December 8th 2015?

I03: Well as I think I mentioned at the time, following comments: one, I think it was too long erm, too, there should have been a little bit more explanation because although I was aware of what it was saying I was conscious that somebody perhaps who hadn't had that background in it would not follow what you were trying to portray in it. I think I'd also say that I don't think you brought out the work that you've really done so far, I don't think it gave credit to what you've done so far. I mean clearly the graphics are impressive, and so is the production itself so I have nothing to say regards to that. I mean god knows how you do it but you've done it and well done so from that perspective it's good but it didn't really hit the point with me.

IN: A part of the video illustrated a smoother profile in comparison to the current SAM model for the same assets (this is based on replacement of the part rather than the entire AHU). Results have shown that there could be more than £1m in surplus budgeted for lifecycle at [redacted]. How would visualising how this lower figure has been achieved via the PALM model impact your level of confidence in the lifecycle of air-handling units at [redacted]?

IO3: I have to see that doesn't surprise me, what does surprise me is that CIBSE provides guidance to such a level of detail. Okay so let's just take that point then, so what you're saying is the consequence of what we're looking at here (picks up cumulative lifecycle chart – figure x) is that A, we are removing the big area of expenditure currently in the model, so from a cash flow point of view it looks much better and secondly then the actually from a cumulative point of view you've got more than a marginal saving you've got a £1m saving there. So what 15-20% saving by doing it that way. So your question was, visually how can you show that? So you were showing the AHUs and hot spotting the different parts which needed replacement. I think in truth the graph says a lot. An immediate question anyone would ask when making a decision would be 'hang on, I can't afford that' and maybe what we ought to have on here is the model cash flow against that. So firstly do we have enough money to do that because if that black line (option C) is that same as what's in the model then you could say that you can't actually do the work. So there may actually be a need to delay that. I think what you've gotta do is couple that up with the visualisation so that you're looking at the AHU and you've got the graph sitting alongside it and so from that perspective the starting point would almost be a black box of the whole unit and what we are saying at the moment is that were gonna lift the whole damn thing out and replace it, well that ain't gonna happen – which is that line there (Option C). So your next stage is to say were taking this bit, this bit, this bit, this bit, and you're starting to get an appreciation to somebody who doesn't know about and air-handling unit and that actually I can now understand the rationale for doing it like that (Options 1-4).

IN: The model shows what is being proposed to be replaced via an RGB visual over time. The profile is underpinned by real cost data collected across HCP hospitals. So, how do you believe the model better informs decision-making at a strategic level?

I03: Well I think it better informs it because you're starting to get out a theory and you're starting to go down into the detail and it's backed up by actual information. I have to say, what I don't know where CIBSE gets their information from. So the stuff that's out there, where does that come from? Manufacturers who say yeah this is what I'm thinking? And where are the manufacturers getting that from? You know, is it true data they're using or some guy in the office saying 'oh yeah I remember when we did that, that'll last…' you know, some old sage who, don't get me wrong has probably got a good feeling of it but who actually is it really accurate information? So that to me is the big difference. Here we are splitting it down and we're starting to get real data rather than assumed data. Thinking about the other aspect involved here is risk. And by that what I mean is if you were to say generally we think this item of kit will last erm 5 years and we'll replace it after 5 years what I think we're saying is we think that piece of kit is gonna last 5 years and we're just gonna take the whole thing out and put a new one right in. So what does that mean, you've got another 5 years at pretty low risk. So what I think you would need to overcome if you were making the decision is by doing it like this and not having the wholesale replacement am I actually increasing my risk or not? Because in theory if you've got something brand new in there you're starting again. So statistically perhaps replacing a part could increase the risk of the entire system. I suppose if you are breaking it down into 1300 or so items, you can probably start to show those areas which are high risk. So say we've assumed said failure of said points, in future you can assess whether this was correct and if not what the other bits and pieces which actually fail sooner are. So from a critical spares point of view, we'll know what parts we need to hold. So as I mentioned, from a risk point of view, it just starts to reduce that risk.

IN: Removing yourself from the current situation at [redacted] (as we are all aware of the difficult times the project faces at current), would similar visual modelling techniques increase confidence in your ability to be able to suggest distributions of the surplus lifecycle attributed to these assets?

I03: Umm, I think to be frank, in itself, you know put the visual model up on the screen by itself I would say no it doesn't in itself. But I think it is an aid to a whole suite of stuff that says this is how it's done. So I think from this point of view I see it as an aid when people are sat round the table and whether that, quite frankly, is investors, whether it's probably not the TA, because the TA tends to be a technical person that is down in the weeds there that knows it all anyway. But I do think that it would help with regards to the funders so the actual banks rather than the TAs. But again from a TAs perspective maybe it's a tool he can use in convincing and talking with his bosses who are the funders so I think as I say, I see it as not an end in itself but as an aid in the whole process about giving confidence.

IN: Do you think there is a need for such visualisation techniques to advance the field of lifecycle costing and management? If so, why?

I03: Need. In other words, will it advance without it? Is it absolutely essential to it, no I don't think it is, I'll be absolutely honest? As I say, I think it's a good aid. But it adds to the melange of things which tell the whole story. I mean in time actually, thinking about it, in time it could be the sort of vehicle that…the core in which you could potentially start adding things on around it I suppose, whereas at the moment it's part of it, in time it's actually the core of it and you're adding stuff around it so it actually is the main driving engine potentially for it.

IN: Do you feel that the model helps to increase clarity to the process of lifecycle? If so, which stakeholders do you believe could benefit from such a tool?

I03: I think yes it does and it's the stakeholders who are the non-technical stakeholders. I think that's it, I mean you speak to some people and say an air-handling unit and they don't know what the hell you're talking about so some people are actually at that level so I think that firmly it's the non-technical, it's the financial people that are involved and stand to gain something from this.

IN: In terms of winning work and displaying our skill set as a business, do you believe that this tool could be used as part of a business proposition for HCP going forwards?
I03: Definitely. Yeah, without a doubt. I mean I think from a selling point of view I think it's ideal. It's great. The danger is that you don't have enough back up, so having the combination of it all as you do it works well. Visual is a good focal point and this is excellent in that regard